USING ORBITAL ALTIMETRY AND OCEAN COLOR TO CHARACTERIZE HABITAT OF SPERM WHALES IN THE GULF OF MEXICO

A Thesis

by

JULIA ELIZABETH O'HERN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the
degree of

MASTER OF SCIENCE

December 2007

Major Subject: Oceanography

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Approved by:

Chair of Committee,	Douglas C. Biggs
Committee Members,	Matthew K. Howard
	Bernd Würsig
Head of Department,	Piers Chapman

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ABSTRACT

Using Orbital Altimetry and Ocean Color to

Characterize Habitat of Sperm Whales in the Gulf

of Mexico. (December 2007)

Julia Elizabeth O'Hern, B.A., Cornell University

Chair of Advisory Committee: Dr. Douglas C. Biggs

On Mesoscale Population Study cruises during summers 2004 and 2005 aboard the sailboat *Summer Breeze,* researchers from the Sperm Whale Seismic Study (SWSS) surveyed for sperm whales along the continental slope of the northern Gulf of Mexico. SWSS scientists tracked 35 groups of whales during these two summers, recording locations where they did and did not encounter whales. Whales were encountered during both summers at approximately the same frequency (19 groups in 38 survey days in 2004; 16 groups in 29 survey days in 2005), but fluke photo-identifications indicated that 85% of individuals encountered during summer 2005 had never been previously identified in the Gulf throughout 10 years of cetacean research. Composition and distribution of these groups also varied between summers. Oceanographic conditions at the edge of the continental shelf differed between 2004 and 2005, which may have modified the usual trophic cascade that begins with near-surface primary production to create local aggregations of prey at the depths where sperm whales forage.

Sperm whales are apex, mesopelagic predators, but have been shown to associate with surface primary productivity over large spatial scales and time scales of months to years. The purpose of this thesis was to look for relationships between sperm whale presence and surface oceanography on smaller spatial and shorter temporal scales. Surface ocean color from NASA's Moderate Imaging Spectroradiometer (MODIS) and surface dynamic height from NASA's Earth orbital altimeters were evaluated to assess habitat occupied by sperm whales. Passive acoustic monitoring along transect lines for sperm whale clicks permitted determination of sperm whale presence and absence.

Sperm whale encounters were in general associated with negative sea surface height and enhanced sea surface chlorophyll (SSC), especially in or near areas where local SSC anomaly was produced by cyclone induced upwelling of nutrients or from coastal water advected off-margin. During summer 2004, SSC was generally high all along the upper continental slope whereas summer 2005 saw relatively low SSC along the upper continental slope. Whales encountered in this study were most highly correlated with SSC two weeks after the initial development of locally highest-SSC anomalies.

ACKNOWLEDGEMENTS

The completion of this thesis would not have been possible without the support of a large number of people. Funding for the Mesoscale Population Study was provided by Marine Minerals Service under contract 1435-01-02-CA-35186. I would like to thank the members of my committee for their counsel and assistance. Dr. Doug Biggs, my committee chair, for his guidance in developing the direction of my research and this manuscript. Dr. Matt Howard provided invaluable instruction in the computer programming necessary to obtain and analyze satellite data, as well as the interpretation of that data. Dr. Bernd Würsig advised me throughout the writing of this thesis and I am grateful for his insight.

Data collected as part of the Mesoscale Population Study were made available to me by Dr. Jonathan Gordon and Dr. Christoph Richter. I could not have conducted the analyses in this thesis without the generous time that Dr. Gordon and Dr. Richter took to provide their datasets.

I would also like to thank my friends Alyson Azzara who has watched out for me and Kelly Cole who helped me with the computer code.

Finally, I could not have entered graduate school or the field of oceanography without the support and patience of my family. I am immensely fortunate to have parents, a grandmother and a sister and brother who encouraged my peculiar passions and put up with me. I am lucky to have parents who gave me a home, community, friends, family, and a church that defended me as much as challenged me. I could not have found my way without them.

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CHAPTER I

GENERAL CHARACTERISTICS OF SPERM WHALE HABITAT IN THE NORTHERN GULF OF MEXICO

Introduction

Satellite remote sensing is a powerful tool for obtaining oceanographic data about the surface habitat of sperm whales and other apex predators. Satellite imagery provides extended temporal resolution and offers wide geographic coverage to researchers studying these active, mobile animals. However, our understanding of the biology and physics of the subsurface environment where these predators forage is still very limited. In order to utilize remote sensing technology to better understand the subsurface ocean, the relevant time and spatial scales of processes that govern the interactions between surface and subsurface physical and biological environments must be well established.

The use of satellite data to correlate physical oceanography with the trophic interactions of the marine life in our oceans is still a relatively new field. To date, most studies of cetaceans and their physical habitat have focused on correlating variations in distribution and abundance of whales with variations in sea surface temperature (Hooker et al. 1999; Baumgartner et al, 2003; Keller et al, 2006). With the development of satellite altimeters that measure sea surface dynamic height (SSH) and ocean color sensors that measure sea surface chlorophyll (SSC) standing

This thesis follows the style and format of *Journal of Applied Ecology*.

stock, a more detailed picture of the dynamic environment in which whales live has begun to emerge.

As part of Photo Identification and Mesoscale Population Study (MPS) cruises during summers 2004 and 2005 aboard the 46-foot sailboat *Summer Breeze,* researchers from the Sperm Whale Seismic Study (SWSS) surveyed for sperm whales along the continental margin of the northern Gulf of Mexico. The goal of this thesis was to use ocean color and satellite altimetry data to describe the surface habitat in which these whales were observed, and thus discern environmental preferences among whales encountered by the *Summer Breeze* crew. Figure 1 shows encountered whales plotted over composited satellite data for the study area.

Satellite derived SSC values, SSH values and the corresponding surface velocity vectors derived from SSH for each whale encounter were compared to those of adjacent locations where whales were not encountered to better describe habitat use in the Gulf of Mexico.

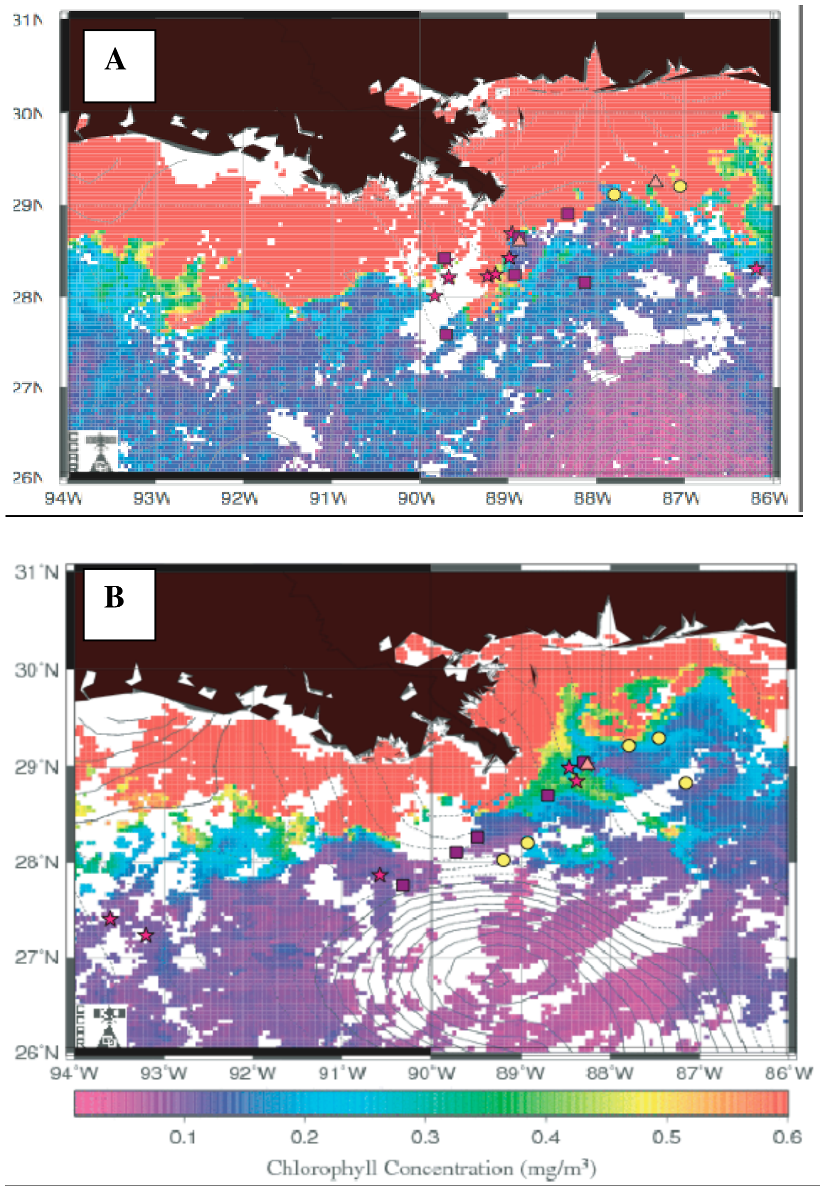

Figure 1. Distribution of Encountered Whales. A: 2004 & B: 2005. SSH and SSC composite plots from the midday of each cruise. Positive SSH is denoted by solid lines and negative SSH by dashed lines. Pink stars indicate mixed groups containing re-identified individuals, mixed groups containing only new individuals by green squares, male bachelor groups with re-identified individuals by orange triangles and yellow circles indicate male bachelor groups with only new individuals.

Remote Sensing

Satellite derived data have greatly improved the ability of researchers to describe how physical environmental parameters vary in time and space. One of the most successful endeavors has been the use of satellite altimetry and satellite observed ocean color to study the response of primary production to mesoscale variations in ocean circulation (Muller-Karger et al, 2005). The Moderate Resolution Imaging Spectroradiometer (MODIS) mounted aboard NASA Aqua and Terra satellites provides images of daylight-reflected solar radiation and day/night thermal emissions over the entire planet, every day (Vogel, 2005). Clean ocean water strongly absorbs electromagnetic radiation at the red portion of the spectrum and transmits and scatters shorter (blue and green) wavelength light. Chlorophyll *a* absorbs most heavily at these blue wavelengths and transmits green wavelengths. By measuring the intensity of light transmitted back to the satellite from the ocean surface, bio-optical researchers compute concentrations of chlorophyll *a* and are then able to estimate corresponding biomass or standing stock of phytoplankton (Nezlin, 2005).

Conversion of ocean reflected solar radiation to concentrations of surface chlorophyll is an ongoing and complicated effort. Among the calibration criteria, according to Howard and Kenneth (1999) are: 1) the computation of a relationship between the color of the ocean and the phytoplankton pigment concentration and 2) the development of algorithms to remove the interfering effects of the atmosphere from the imagery.

Satellite altimeters measure SSH by recording the round-trip travel time of microwave pulses from orbit to the sea surface. Anticyclones display a positive SSH anomaly from the mean geoid SSH, whereas cyclones are characterized by negative SSH anomalies. Robert Leben and his research group at the Colorado Center for Astrodynamics Research (CCAR) have created an interactive website that allows users to composite this altimetry data for the Gulf of Mexico to produce visual representations of the Gulf's eddy field (http://argo.colorado.edu/~realtime/welcome/) and provided access to their raw altimetry data for quantitative analysis.

Sperm Whale Distribution and Behavior

Sperm whales are large mesopelagic predators, feeding mainly on cephalopods (Clarke 1996). Studies in the tropical and subtropical Pacific Ocean have demonstrated that much of sperm whale behavior varies according to prey availability. Whitehead (1996) reported that equatorial Pacific sperm whales over the course of 12-hour observation periods traveled just 16 km when feeding success was high and 20 km during times of moderate success. However, Whitehead noted that horizontal displacement of distances greater than 40 km in 12 hours were observed when feeding success was extremely low. During SWSS fieldwork, Gulf of Mexico whales that were followed closely for 12-50 hours in the region south of the Mississippi River Delta had an average daily horizontal displacement of 35 km in 2004 and 50 km/day in 2005 (Gordon et al, in review). Despite the interannual difference in average daily horizontal displacement, whales from both summers did tend to zig zag over particular areas, suggesting that in 2004 and 2005 the whales were able to find successful foraging grounds (Gordon et al. in review).

Distribution patterns as well as traveling distance also appear to be related to foraging success. Jaquet and Gendron (2002) determined that sperm whales were randomly distributed in the Gulf of California during 1998 when squid landings were low but were present in 3 super aggregations in 1999 after squid landings had begun to recover. Similarly, Christal and Whitehead (1997) and Palacios (2003) reported that in 1995 male sperm whales appeared to aggregate in local areas around the Galapagos Islands where feeding success was generally high.

The Physical and Biological Habitat of the Gulf of Mexico

During the summer of 2005, Mississippi River outflow was more than one standard deviation below the average monthly discharge in relation to its 25-year mean discharge 1980-2005 (Biggs and Jochens, in review). In 2005 the Loop Current also extended much further north into the Gulf than during summer 2004. These two environmental variables generally kept surface salinity high and chlorophyll low over the upper continental slope in summer 2005.

As demonstrated by Leben (2005), the extent of Loop Current penetration into the eastern Gulf varies markedly from year to year, and this inter-annual variability is important in establishing the basin-wide eddy field. Anticyclonic mesoscale eddies are shed stochastically from the Loop Current in the eastern Gulf. These eddies then propagate into the central and western Gulf where they may generate, or be modified by interaction with cyclonic features (Biggs et al. 1996). Eventually, these anticyclonic warm-core eddies will spin down or be cleaved into even smaller eddies (Schmitz et al. 2005). During this process, sport fishermen often find large pelagic predators such as tuna and marlin in local abundance in the surface waters of frontal zones separating the eddy periphery from adjacent slope water (Biggs et al. 1988).

The larger Loop Current eddies (LCEs) have diameters of approximately 300-400 km and translational speeds of 3-6 km per day. When they reach the central Gulf, LCE rotation periods are typically 7-10 days. The smaller cyclones and anticyclones of 40-150 km diameters found in addition to the LCEs are characterized by somewhat longer rotation periods of 10-20 days, but because these smaller eddies are often located in shallower water depths along the continental margin (i.e., closer to the shelf-slope break), they are responsible for much of the off-slope transport of surface water (Hamilton and Lee 2005). Such shelf eddies can advect high chlorophyll, low-salinity shelf water offshore (Belabbassi et al, 2005).

Mississippi River discharge contributes nutrients mainly to the upper 15m of the water column, below this 15m depth, nutrients are introduced to the water via uplift generated by cyclonic rotation and by other cross isopycnal mixing processes. Divergence may be enhanced in the vicinity of cyclone-anticyclone pairs where horizontal surface flow is enhanced. The degree of vertical uplift appears to be determined by the strength of the corresponding anticyclone (Belabbassi et al 2005).

In this chapter of my thesis I will show that sperm whale habitat surveyed during 2004 and 2005 varied both along SWSS cruise tracks and summers. The distribution and behavior of whales encountered during both summers will be linked to patterns of oceanographic variation in the Gulf of Mexico. To summarize the detailed results that will follow, sperm whales were generally encountered during both summers in green, productive waters, though this correlation was most significant when a time lag of two weeks was considered. Bachelor male groups exhibited the strongest association with green water, usually lagging an area's highest SSC by just 1 week. The locally higher SSC values at sperm whale encounter locations were largely produced by the passage of cyclonic eddies which uplifted nutrients from below the surface.

In 2005 when SSC values throughout the study area were 1.4-4 times lower than in 2004, there was a greater difference between SSC at the locations of whale encounters versus no-encounters. Also, defecation rates were reduced, fewer calves were observed, median group size was reduced, more juvenile males were encountered, and a greater number of "new" individuals were identified. The re-identified whales in 2005 were generally encountered in waters of much less SSC than "new" whales, whereas re-identified whales in 2004 did not exhibit any preference for green water that was different from their "new" whale counterparts. These changes in the types of sperm whales encountered at varying oceanographic conditions suggest that Gulf of Mexico whales may be selecting different habitat based on their activities and social units.

Null Hypotheses

1) There is no statistical difference in the average SSH and/or SSC values for areas of sperm whale encounters compared to other locations within the same sailboat searched area of the Gulf of Mexico.
    a. I expect, however, that whales were more likely to be encountered by the sailboat in locations where SSH was lower than average and SSC was higher than average during the one to four weeks preceding the sailboat encounter with whales.
    b. I also expect that when sperm whales were encountered in areas of low SSH and high SSC, the time history of chlorophyll levels during the one to four weeks preceding the sailboat encounter will be important.
2) There is no difference in groups of whales encountered per day in summers 2004 and 2005.
    a. I expect, however, that there will be differences in encounter rates west and east of 88.5^{o}W due to the proximity of Mississippi River discharge and northern periphery of the Loop Current.
    b. I also expect that encounter group composition and sizes may vary between summers due to interannual variations in river discharge and northward intrusion of the Loop Current into the Gulf.

Methods

Sperm Whale Surveys

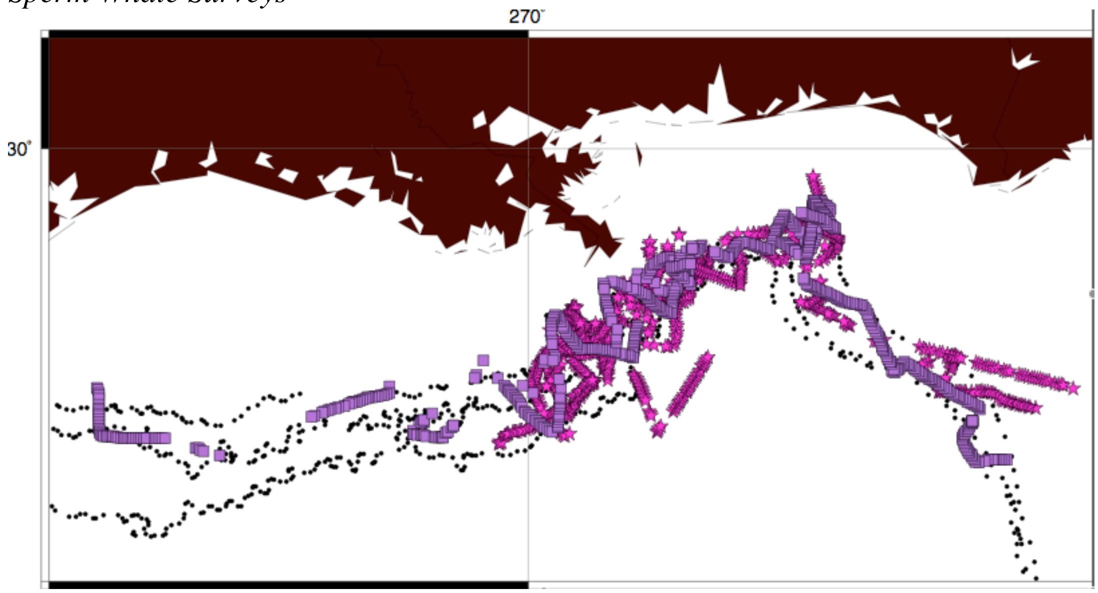

Figure 2. SWSS MPS Acoustic Survey Effort. Black dotted lines indicate the 500 m, 1000 m, and 1500 m isobaths. Pink stars indicate acoustic listening stations during the 2004 cruise and purple squares indicate acoustic listening stations during the 2005 cruise.

Mesoscale Population Study (MPS) surveys for sperm whales in the Gulf of Mexico were conducted along the continental margin during June-August of 2004 and 2005. The platform was a 46' sloop sailboat *Summer Breeze*. Surveys focused effort between the 500 m and 1500 m isobaths. Whales were primarily encountered acoustically using stereo towed hydrophone arrays fabricated by Ecologic UK.

Hydrophones were monitored every 15 minutes for one minute while the sailboat was in survey mode (see "acoustic listening stations" locations in figure 2). Once MPS researchers encountered a group of sperm whales, they followed the group as long as possible or until all individuals in the group were photographed. The sailboat then moved to another area and resumed survey. Males were distinguished from females by estimated body length (Jonathan Gordon, communication). Table 1 shows that survey efforts were 38 days in summer 2004 and 29 days in summer 2005.

Table 1. Summary of Acoustic and Visual Survey Effort on *Summer Breeze* Cruises

Year	Dates of Field Work	Longitude range of continental margin surveyed	Survey Days	Sperm Whales (or groups of whales) sighted
2004	June 20 - Aug 15	90.5^{o} – 84.5^{o} W	38 days	19
2005	June 13 – Aug 3	93^{o} – 85^{o}W	29 days	16

Along Cruise Track Average Chlorophyll Values

The 2004 and 2005 cruise track and whale encounter locations from the *Summer Breeze* cruises were provided by Jonathan Gordon. Along-cruise track chlorophyll-*a* averages were computed using a subroutine written by Chuanmin Hu at the University of South Florida (USF) to read chl*a* values from daily pass hdf MODIS files. The USF program was adapted at TAMU to read a daily MODIS hdf Gulf of Mexico (GCOOS) image (http://modis.marine.usf.edu/weekly/gcoos/gcoos.index.html) for every day of the 2004 and 2005 cruise tracks, as well as reading six other images for each day of search effort. The set of six additional images represent discrete time-lag periods from each day of search effort, hereafter referred to as the zero days. The time-lag images are daily images from approximately one week, two weeks, four weeks, and sixteen weeks before and after the sailboat was present at the given locations along its cruise track (Table 2).

Table 2. Time Lag Categories

Time Lags	Chl_0 SSH_0 SSS_0	Chl -1 SSH -1 SSS -1	Chl -2 SSH –2 SSS -2	Chl -4 SSH –4 SSS -4	Chl -16 SSH -16 SSS -16
Satellite image describes SSC, SSH, or SSS within:	0-2 days of ship location	6-10 days previous	12-16 days previous	28-32 days previous	118-122 days previous
Time Lags		Chl +1 SSH +1 SSS +1	Chl +2 SSH +2 SSS +2	Chl +4 SSH+4 SSS +4	Chl+16 SSH+16 SSS +16
Satellite image describes SSC, SSH, or SSS within:		6-10 days after	12-16 days after	28-32 days after	118-122 days after

Chlorophyll and SSH averages were calculated for each acoustic encounter marked in the cruise track records. In order to address the issue of pseudo-replication, all SSC and SSH values obtained from a single tracking period were averaged together. One tracking period was the time in which *SummerBreeze* followed a single group of whales. In any group, there may have been individual whales leaving and joining intermittently, so groups were identified to the best of the abilities of the *SummerBreeze* crew (Table 1).

Each location from the cruise tracks does not necessarily have a corresponding chlorophyll (SSC) value for each time lag, because satellite images are incomplete data sets and SSC values are only calculated for locations where the satellite was able to "see" the ocean color. Although the pixel resolution of these satellite images is about 1x1 km, SSC values were computed based on an average of three-by-three pixel boxes. SSC values were converted to a base 10 log scale to calculate geometric means for SSC at each time lag. A log scale was chosen for comparison of SSC values based on the work of Campbell (1995) and Doney et al (2002) to better represent the lognormal optical variability of the surface ocean**.**

Along Track SSH and Surface Velocity Vectors

Satellite altimetry data were collected and processed by the Real-Time Altimetry Project at Colorado Center for Astrodynamics Research. Altimetry data were selected for the same time lags as that of CHL but were 0.25º x 0.25º gridded at CCAR before being processed in this analysis. Eight day composites, using the day of interest as the median day were used to temporally average the SSH data. Averages were calculated for each time lag for locations of whale encounters as well as no encounters.

Several scripts written using Mathworks MATLAB software enabled processing of output generated from the hdf images and reader program.

Along-Isobath Average Chlorophyll and SSH Values

Along-isobath chlorophyll values were derived using the same hdf reader program previously described. SSH means were also calculated from the CCAR dataset. To compute the chlorophyll averages along the isobaths, I searched for the best late-June, generally clear-sky image for each summer. I chose Julian day 181 as the zero day image for 2004 (fig. 1A) and Julian day 184 for 2005 (fig. 1B) and then averaged the chlorophyll values from the zero day image with the values from its six time lapse images. In total, 7 days of satellite obtained chlorophyll values were averaged each summer along the length of the 500, 1000, and 1500 m isobaths in the northern Gulf, from longitude 95^{o}W to 84^{o}W, to compute the along-isobath average chlorophyll values.

Correlation coefficients were calculated using the Matlab CORRCOEF function. These correlations represent the zeroth lag of the normalized covariance function. P-values were used to test the hypothesis of no correlation. They represent the probability of obtaining a correlation as large as the observed value by random chance, when the true correlation is zero. Unless otherwise qualified in the text, correlations were considered significant when $p \leq 0.05$. Some correlations for which $0.05 < p < 0.10$ are also presented and discussed.

Modeled Sea Surface Salinity

Sea surface salinity (SSS) values were hindcast for MPS cruise track locations using an experimental real-time intra-Americas sea ocean nowcast/forecast system for coastal prediction developed by the U.S. Naval Research Laboratory (IASNFS). The model derives results from the Navy's global atmospheric model, the Navy Operational Global Atmospheric Prediction System (NOGAPS). IASNFS produces a nowcast as well as 72-hour forecast of sea level variation, 3-D ocean currents, temperature and salinity (Ko et al 2003). This system utilizes a 1/24º, 41-level, data assimilating model derived from the Navy Ocean Model (NCOM) The nowcast is generated by performing a 72-hour hindcast, restarted from the previous day's nowcast minus 48 hours. During this nowcast, the ocean model is continuously assimilating 3-D ocean temperature/salinity analyses produced by MODAS. An incremental adjustment scheme with vertical weighting estimated from relative errors of the model is applied to data assimilation. Satellite altimetry (GFO, Jason-1, ERS-2) and AVHRR sea surface temperature are employed by MODAS to make a 3-D temperature and salinity analyses. Cruise track locations for both summers at each time lag were run through this model for me by Dr. D. S. Ko to obtain an SSS output. These SSS hindcast data were then averaged for whale encounter locations as well as for survey locations where whales were not encountered.

Results

Mesoscale Circulation

Surface flow along the cruise track during survey efforts was generally southeast (off-margin) during 2004. In fact, during summer 2004, mean flow was off-margin for all time lags from one month before survey to one month after survey. The only difference between negative and positive whale encounter locations occurred at a time lag of one month before and after encounters. At this time lag, whale encounter locations still experienced off-margin flow while mean flow at no-encounter locations were experiencing on-margin flow.

During 2005, survey efforts were conducted during times of mean northwest or on-margin flow. But at time lags of 4 weeks before, 2 weeks before, and 1 week after, flow was generally off-margin along most of the cruise track.

Sea Surface Height

Cruise track mean SSH was similar in both summers. In 2004 the along-track mean SSH was –8.2 cm and in 2005 it was –7.1 cm. Mean SSH in an area 4 weeks before the sailboat surveyed the area was on average –4.6 cm during 2004 and in 2005 it was -3.5 cm. These negative SSH values are diagnostic of the cyclonic side of frontal boundary locations between cyclone-anticyclone eddy pairs. As will be shown in the section on sea surface chlorophyll, the negative relationship between SSC and SSH indicates locally higher SSC was found in the upwelling, cyclonic portion of these frontal boundaries.

Whales were encountered in summer 2004 in areas where SSH ranged between –15.1 cm and –2.0 cm with a mean SSH of –8.0 dynamic cm. No-encounter locations covered a much wider range of –23.6 cm to 1.0 cm but had similar mean (–7.5 cm). During summer 2005, SSH of whale encounters ranged from –12.6 cm to +1.2 cm (mean SSH was –4.5 cm). Locations where no whales were encountered in summer 2005 had an SSH range of –25.1 cm to +1.2 cm (mean was –6.0 cm).

Figure 3 shows that SSH generally became progressively more negative, i.e. more cyclonic in rotation, at each point along the cruise track from one month before survey efforts to one month after survey.

Figure 4 shows that in 2004 there was a near linear increase ($r^2 = 0.92$) in surface velocity at locations of whale encounters from 4 weeks before to 4 weeks after contact. The average surface velocity at whale encounter locations 4 weeks before whales were encountered by the MPS cruises in that area was 9 cm/sec. Four weeks after

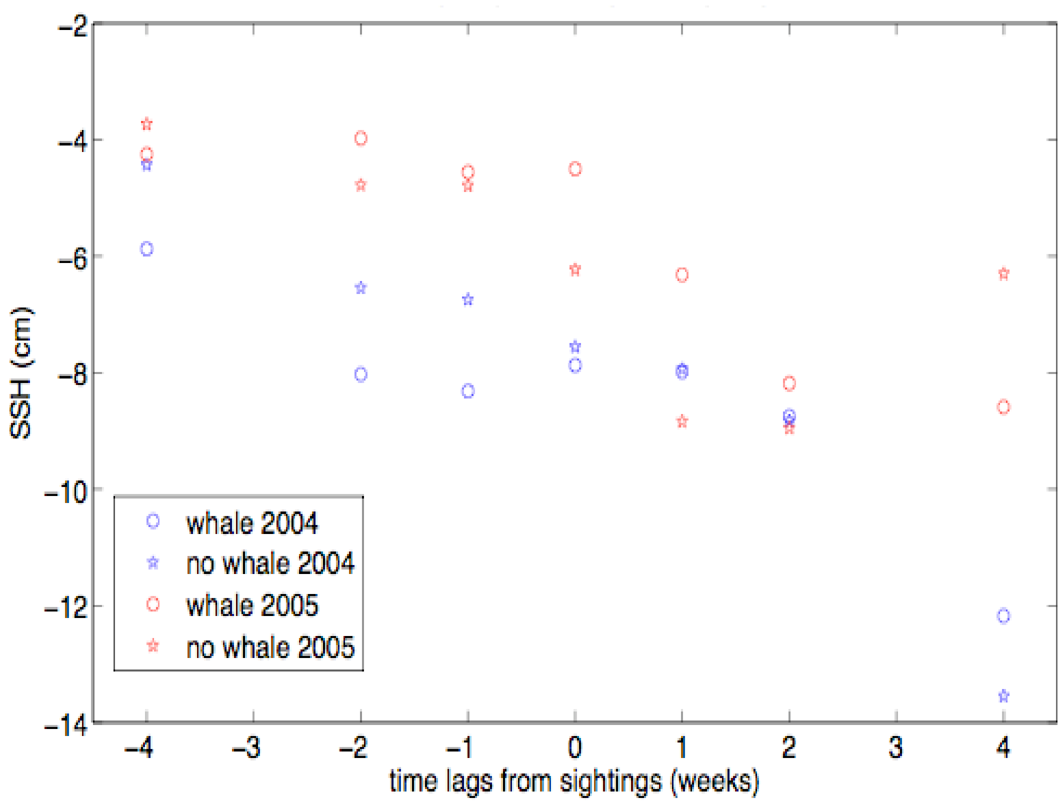

Figure 3. Summary of Change Through Time in SSH Along 2004 and 2005 Cruise Tracks.

Velocity of Surface Circulation

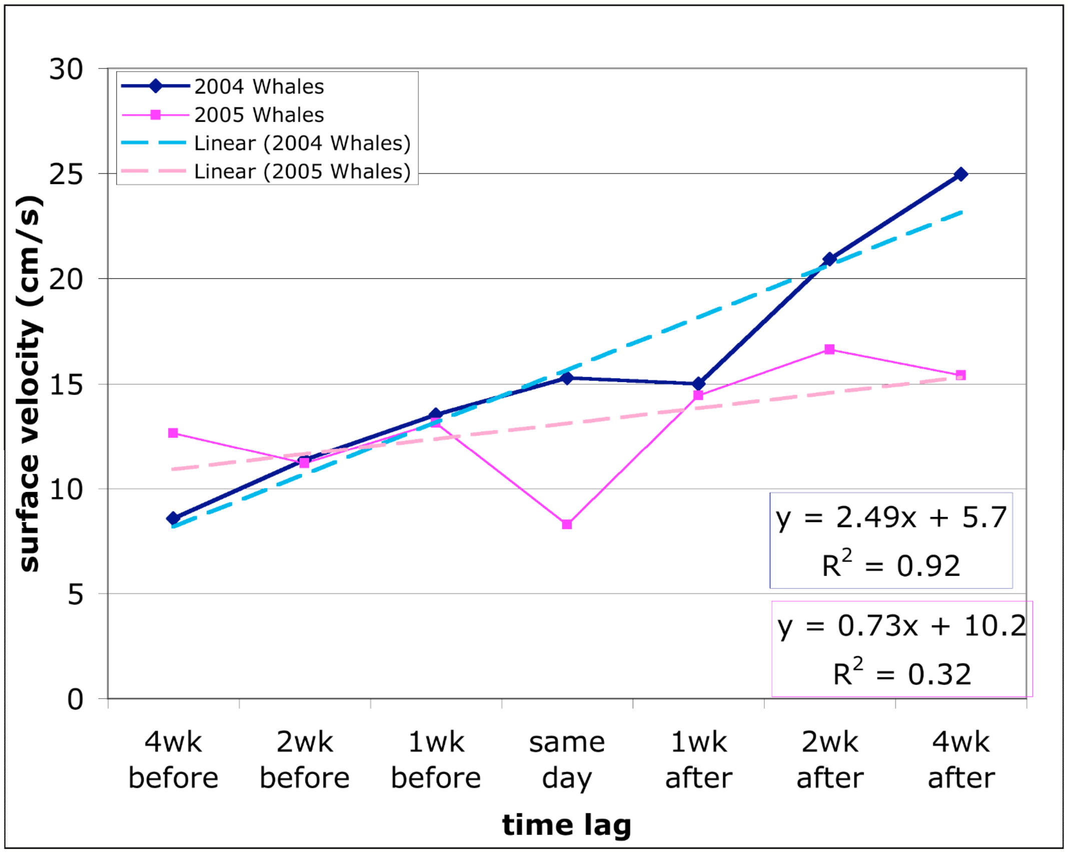

Figure 4. Mean Surface Velocity at Whale Encounter Locations

encountering whales in an area, the average surface velocity of that area had increased almost 3 fold to 25 cm/sec.

In summer 2005, the time rate of increase in surface current velocity at whale encounter locations was more variable. Mean velocity was 13 cm/sec 4 weeks before whale encounters, but this decreased to 8 cm/sec on the day of whale encounters and then increased again to average 15 cm/sec 4 weeks later.

Cruise Track Sea Surface Salinity (SSS)

On average, hindcast sea surface salinity (SSS) was higher along the 2005 cruise track than the 2004 track. Negative whale encounter locations during 2005 had greater SSS than positive encounter locations. SSS was about equal at negative and positive whale encounter locations during 2004.

During 2004, SSS was also about the same at negative and positive whale encounter locations for each time lag. During 2005, the negative encounter locations had greater average salinity than positive encounter locations when time lags of ±2 weeks were considered.

Sea Surface Chlorophyll

In mid-June 2004, SSC along the 1000 m isobath 95-84°W averaged 0.19 mg/m^3 or about 1.4 times higher than the mean of 0.14 mg/m^3 in mid-June 2005. Along the 2005 cruise track, the mean SSC was 0.16 mg/m^3 or about the same as the mean for the entire 1000 m isobath. But along the 2004 cruise track the mean SSC was 0.59 mg/m^3, which is three times higher than the mean for the entire 1000 m isobath. SSC analyses conducted during 1998-2000 at DGOM stations between 86º-90º and 300 m-2000 m found a geometric mean of 0.54 mg/m^3 SSC.

Greater than average SSC concentrations seemed to result when eddies interacted with the continental margin and/or with each other, over time scales of approximately one month. Throughout both summers, highest SSC values along the cruise tracks were associated with SSH values between –15 cm to +4 dynamic centimeters (Figure 5). In summer 2004, highest SSC in this range of SSH exceeded 10 mg/m^3; in summer 2005, highest SSC reached 2 mg/m^3.

The strongest correlations between SSH and log SSC occurred at time lags of 1week and 4 weeks (correlations were -0.52 and -0.49, respectively; p-values were both < 0.01). Log SSC was also correlated with surface velocity. SSC lagged behind u vector surface flow (the east-west velocity vector component) by one week, but in this case the correlation was positive (correlation was +0.29; pvalue < 0.01). The positive correlation indicates that higher CHL was associated with eastward surface flow. Finally, log SSC also lagged behind v vector surface flow (the north-south velocity vector component) by 1 week (correlation was -0.23; p-value = 0.02). The negative correlation indicates higher SSC was associated with southward flow.

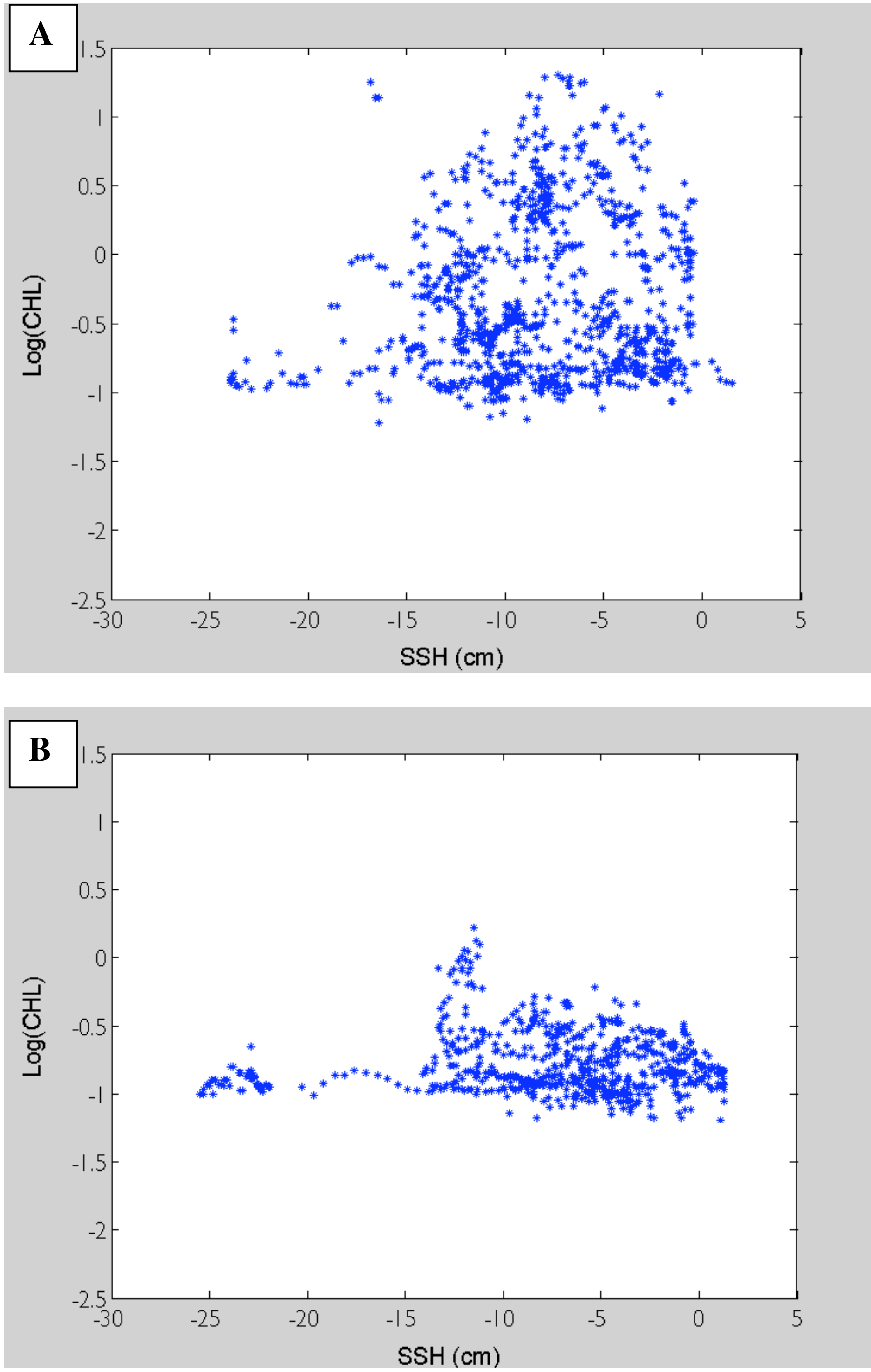

Figure 5. Cruise Track SSC vs. SSH. A) 2004, and B) 2005

To further investigate relationships between surface physical oceanography and SSC, log(SSC) values were divided along a natural break between low and high dynamic range of SSC. The natural break was determined from 100 binned histograms of log(SSC) at the zeroth day time lag. Lower log(SSC) lagged behind SSH by 1week (correlation -0.49; p-value <0.01) and 4 weeks (correlation -0.32; p-value = 0.01) while higher log(SSC) lagged SSH by 1 week (correlation -0.59; p-value = 0.02) to 2 weeks (correlation -0.34; p-value = 0.05). Stronger u vector flow was positively correlated to the lower log(SSC) regime with a time lag of 1 week (correlation was +0.45; p-value < 0.01) but unrelated to the higher log(SSC) regime except with a time lag of 4 months (correlation was +0.59; p-value <0.01). V vector flow was uncorrelated with log(SSC) within the lower log(SSC) regime, but with a time lag of 2 weeks, v vector flow was negatively correlated with higher log(SSC) (correlation was -0.39; p-value = 0.03). Checking for cross-correlation without any time lag, only the lower log(SSC) regime correlated with SSH (correlation was -0.16; p-value = 0.03) and with u velocity (correlation was +0.15; p-value=0.05).

Higher SSC also exhibited significant correlations to the surface currents following the SSC, though these correlations were never as strong as those between SSC and its preceding surface currents. These correlations between SSC and future surface currents were sometimes opposite in signs from those correlations between SSC and preceding surface currents.

SSC and SSH at Locations of Whale Encounters

When locations of whale encounters were added to the cross-correlation matrix, only correlations between lower regime SSC and SSH were significant. Highest correlations with log SSC lagged SSH by 1 week (correlation was -0.53; p-value < 0.01) as expected from a similar correlation along the entire cruise tracks, although log SSC significantly correlated with SSH by a time lag of 4 months (correlation was -0.46; p-value < 0.01). SSC at whale encounter locations was also strongly related to the u surface velocity vector, lagging behind these eastward flows by 4 months (correlation was +0.48; p-value < 0.01).

Cruise Track SSC Through Time

Figure 6 shows that average SSC at each time lag was generally greater at whale encounter locations during 2004 compared to 2005, though none of the differences are significant. In 2005 the no-encounter locations often had higher SSC than those no-encounter locations of 2004, but again, the differences were not significant at the 95% CI.

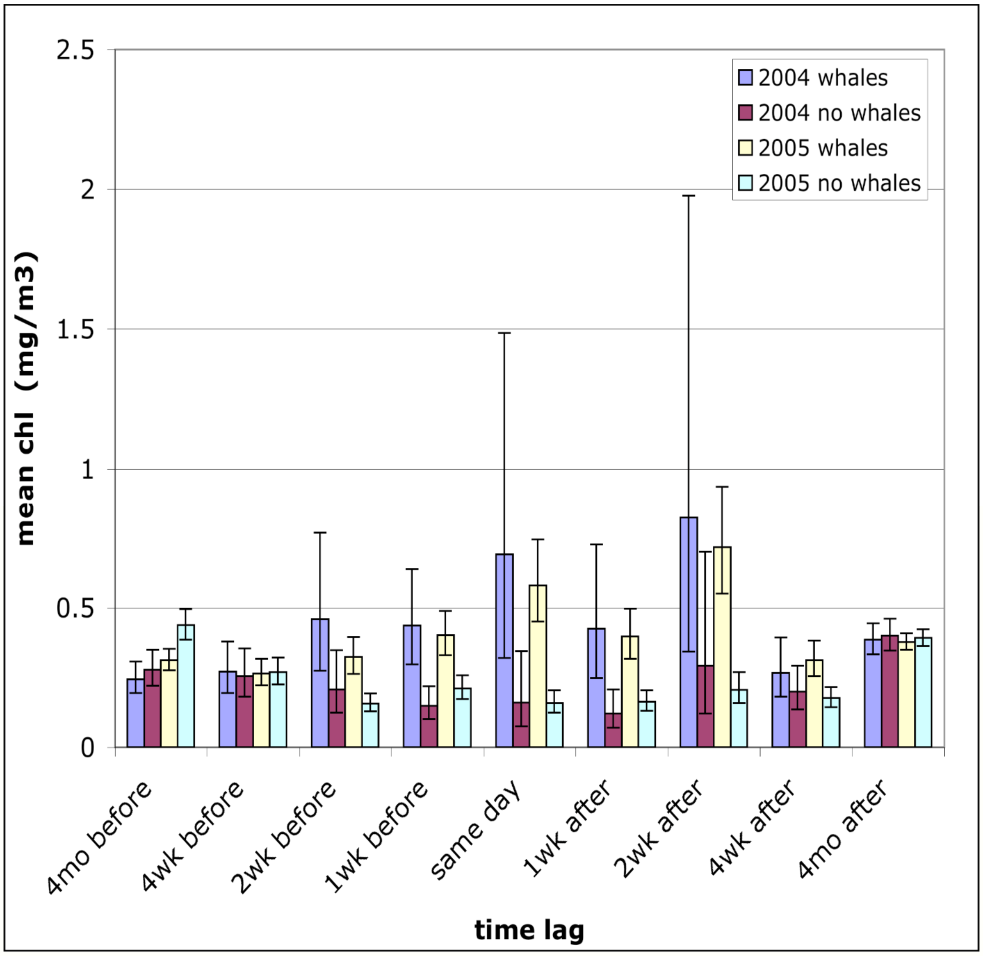

Figure 6. 2004 & 2005 Along Cruise Track Mean CHL vs. Time Lag

When SSC and whale encounters were averaged over both summers, only a time lag of two weeks preceding encounters had a statistically significant positive correlation between log SSC and whale encounters (see table 3: 0.13; p-value =0.05). Although mean SSC tended to increase at the location of a sperm whale sighting two weeks following that sighting, the variation with respect to mean SSC also increased. But four months preceding an encounter, encounters negatively correlated to log SSC concentrations (see table 3: -0.17; p-value=0.02), which likely reflects the late winter-early spring basin wide deepwater bloom of primary production.

Table 3. Log(SSC) vs. whale Encounters: Combined Summers Correlations

	Correlation of log SSC vs. whale encounters	
time lag	corr coeff	p value
4 mo before	-0.17	0.02
4 week before	-0.00	0.95
2 week before	0.13	0.05
1 week before	-0.02	0.82
same day	0.01	0.93
1 week after	-0.04	0.57
2 week after	0.05	0.42
4 week after	0.02	0.75
4 mo after	-0.01	0.93

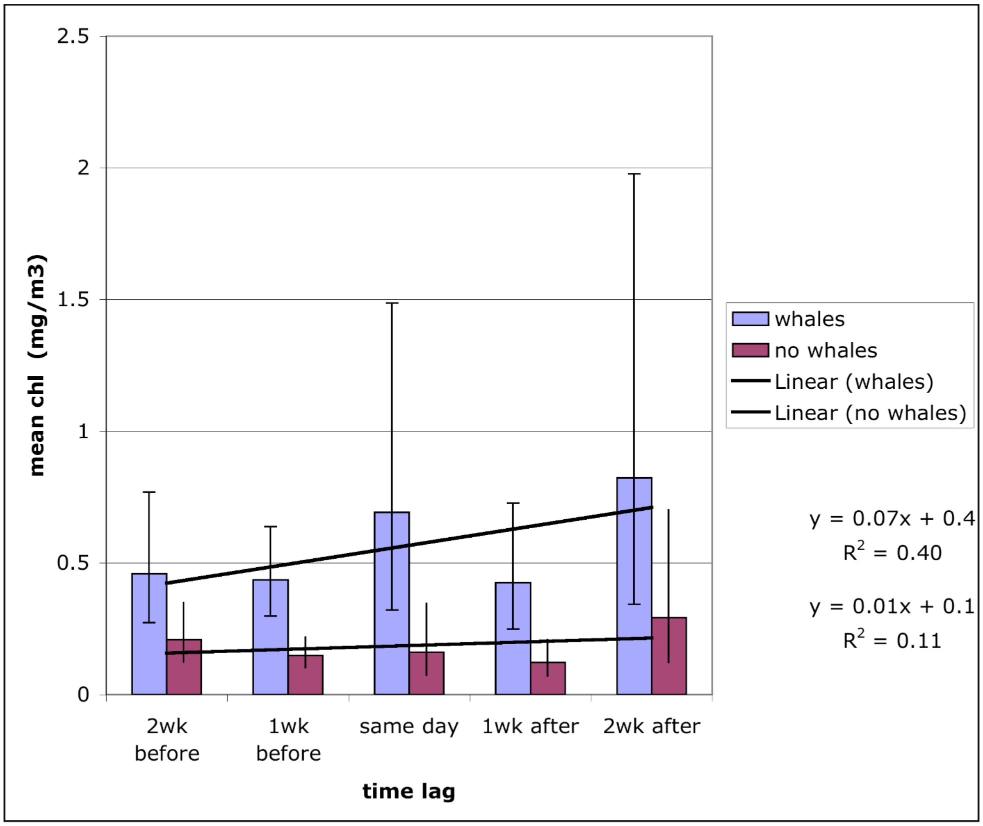

Figure 7. 2004 Along Cruise Track Time Rate of Change in Mean SSC

In 2004, average CHL was higher at whale encounter locations than no-encounter locations at each time lag, although this difference was significant only when a time lag of 1 week before and after whale encounters and SSC is considered (see Figure 7).

During summer 2005 average CHL was significantly greater at whale encounter locations than at no-encounter locations 2 weeks and 1 week before and after whales were encountered as well as at the zero time lags (Figure 8).

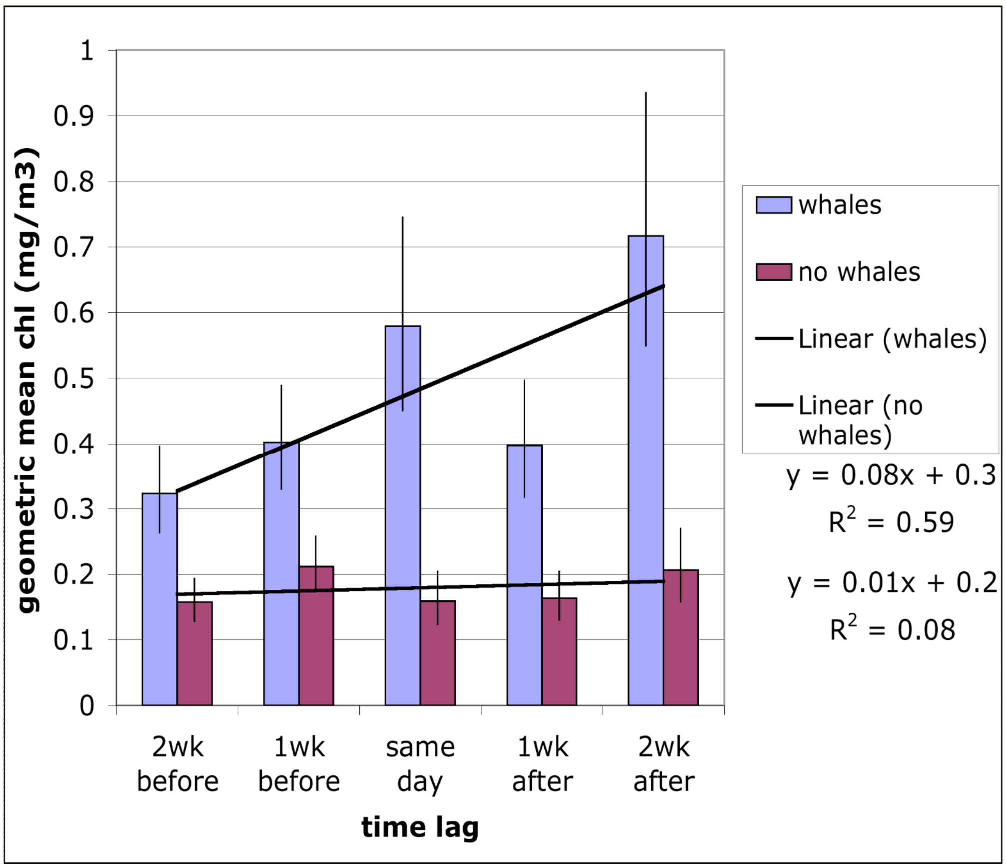

Figure 8. 2005 Along Cruise Track Time Rate of Change in Mean SSC

Table 4 shows that groups of medium sized males were associated with log SSC at a time lag of 1week preceding encounters (0.66; p-value < 0.01).

Table 4. Log(SSC) vs. Group Gender: Combined Summer Correlations

	Correlation of log(CHL)vs. Male and Non-Male Groups	
time lag	corr coeff	p value
4mo before	0.13	0.526
4 week before	0.17	0.368
2 week before	0.27	0.211
1 week before	0.66	0.001
same day	0.03	0.889
1 week after	-0.22	0.271
2 week after	-0.27	0.221
4 week after	0.10	0.629
4 mo after	0.21	0.263

Composition of the Sperm Whale Population

Table 5. Summary of Whale Encounter Groups

Year	Encounter Rate of Groups of Whales/ Day	# Adult Whales Encountered (# Males Identified)	# Calves (% of total)	Mean Group Size (Median Group Size)	% New Whales Identified from Total Whales Encountered	Defecation Rate
2004	0.49	118 (3)	15 (12.7%)	6.10 (13.7)	68%	0.235
2005	0.55	70 (11)	4 (5.7%)	14.7 (6.8)	85%	0.148

Dynamics of the northern Gulf sperm whale population changed between summers as shown in Table 5. Median group size decreased from 13.7 in 2004 to 6.8 in 2005. The majority of individuals comprising these groups, particularly in 2005, were new to researchers (i.e. had not been identified using photo-ids 1996-2003). While roughly equal numbers of bachelor groups were encountered, only 3 individual males during 2004 were identified both as male and as previously encountered by researchers. During 2005, 11 males were re-identified. So, while 32% of whales encountered during 2004 had been previously identified in the Gulf, only 3% of encountered males were re-identifications. In 2005, however, just 15% of encountered whales were previously sighted in the Gulf but 16% of identified males were re-identifications

In 2004 there was no significant difference in SSC between re-identified whale locations and new whale locations or no-whale locations. Interestingly, in 2005 locations where groups with re-identified whales were encountered had significantly less SSC than general whale encounter locations at the 2 weeks before and after, 1 week before and after, same day and 4 weeks after time lags. At the 1week before and after time lags, re-identified whale SSC was also significantly lower than no-encounter locations. These patterns are summarized in Figure 9.

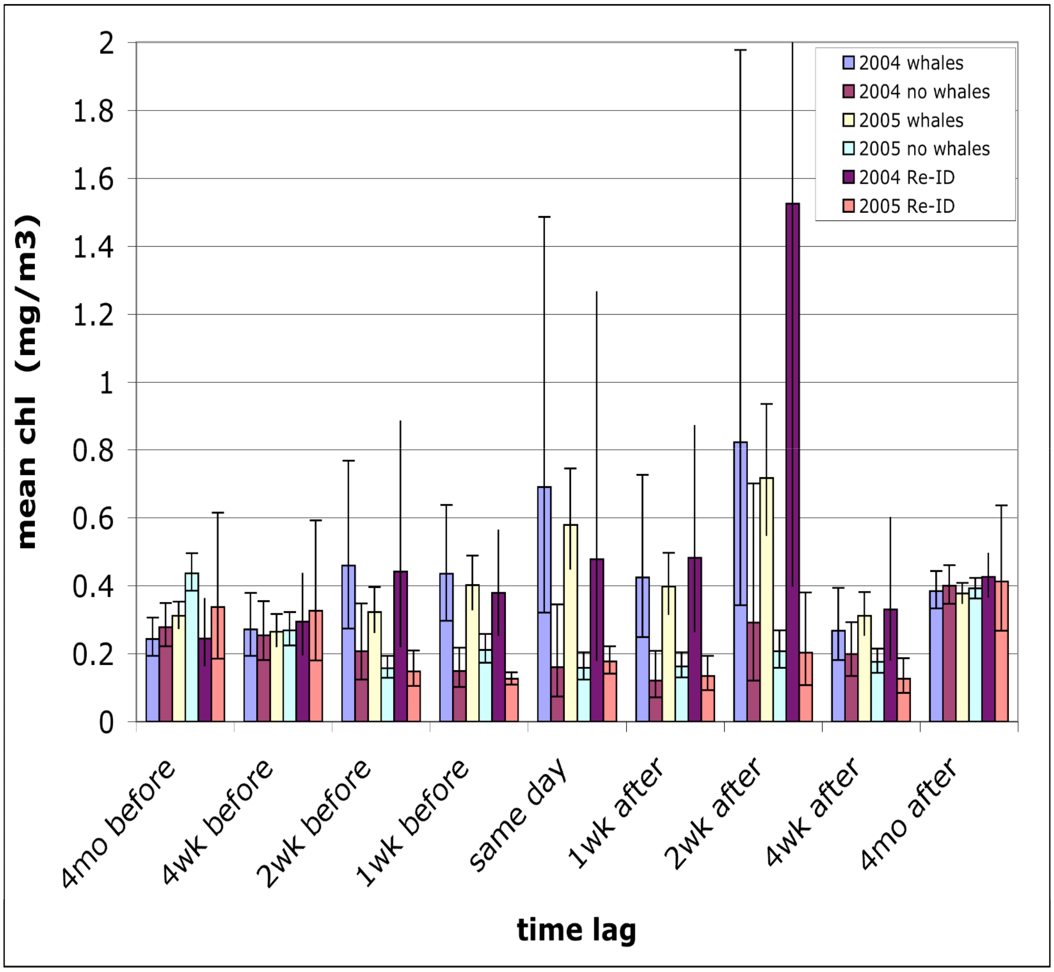

Figure 9. Geometric Mean SSC at Locations of Whale Encounters

Cruise Track Sea Surface Salinity (SSS)

On average, SSS was higher along the 2005 cruise track than the 2004 track. Negative encounter locations during 2005 were also of greater SSS than positive encounter locations. SSS was about equal at both negative and positive whale encounter locations during 2004.

During 2004, SSS was about the same at both negative and positive whale encounter locations for each time lag. However, during 2005 negative encounter locations were only of greater average salinity than positive encounter locations when time lag of ±2 weeks was considered.

Discussion

Jaquet (1996) composited Coastal Zone Color Scanner (CZCS) imagery over several time periods for the tropical Pacific and found that sperm whale abundance was most closely correlated with SSC when SSC was averaged over a period of 4 months. However, the study was not able to estimate the time lag between peak SSC and sperm whale density. By using discrete daily pass images from MODIS, which has higher spatial and optical resolution than CZCS, this study finds a relatively short time lag of just 1-2 weeks between peak SSC and sperm whale encounters. Since these encounters generally took place on the cyclonic side of eddy frontal boundaries, it appears that both physical and biological oceanographic features of an area play an important role in supporting sperm whale populations in the Gulf of Mexico.

In addition to a time lag between peak SSC and sperm whale encounters in the Gulf during summers 2004 and 2005, there is clear geographic segregation between mixed groups of females and groups of male sperm whales in the Gulf. Male groups exhibit a stronger correlation to SSC at a shorter time lag than the mixed groups of females. In 2005 groups with at least one previously identified individual compared to groups with only newly-identified individuals were encountered in areas of significantly lower SSC. Between 2004 and 2005 Gordon et al (2007) reported that there was a 37% reduction in foraging success (as indicated by defecation rates) among encountered sperm whales. There was a similar reduction (30%) in geometric mean SSC along the 1000 m isobath between these summers, which suggests that sperm whales may be effected by changes at the base of the food chain over relatively short time scales.

There are several oceanographic parameters that likely contribute to the make-up of favorable habitat for sperm whales. Belabbassi (2005) showed that SSC concentrations decreased with distance from the coast and depth. Waters more distant from the coast are removed from the riverine and terrestrial sources of nutrients that support primary production. Biggs and Jochens found that sperm whales were closely associated with off-margin surface flows, water that flowed from the coast. For *SummerBreeze's* survey area, easterly currents (flow from the West) were the cross-margin flows carrying riverine discharge. Along the cruise track there was a time lag of 4 months between these cross-margin flows and very high and low SSC. In other words, SSC production was correlated with areas to which nutrient rich water had been advected.

High SSC from the cruise track exhibited a strong relationship to off-margin flow (southerly flow) at a time lag of 2 weeks. Lower regime SSC did not show any relationship to off-margin flow and the time lags between low SSC and SSH were 1 and 4 weeks respectively, whereas high SSC was related to negative SSH at just 1 and 2 weeks. Review of MODIS imagery offers an explanation. Low SSC values persist in an area and correlate with SSH over a month. This is about the amount of time that a cyclone can persist in an area. High SSC degrades first and is linked to cyclonic SSH by just 1-2weeks. From 1week MODIS imagery composites made by Chuanmin Hu at USF (Figure 10), time scales on which SSC persists in the surface ocean can be visualized. In 2004, high SSC color that is being pulled off-slope only persists through images of Julian Days 197-203 and 204-210. The high SSC correlation with SSH is -0.59 at 1 week (p-value = 0.02) but decreases to –0.37 at 2 weeks (p-value =0.05).

Lower regime SSC at the locations of whale encounters lagged cross-margin flows and negative, cyclonic SSH by 4 months. This is the approximate length of time estimated by Sette (1955) for the build-up of three trophic levels in a marine community, or near the trophic level at which sperm whale prey likely feed. SSC at survey locations where sperm whales were not encountered did not exhibit this same 4 month relationship to SSH.

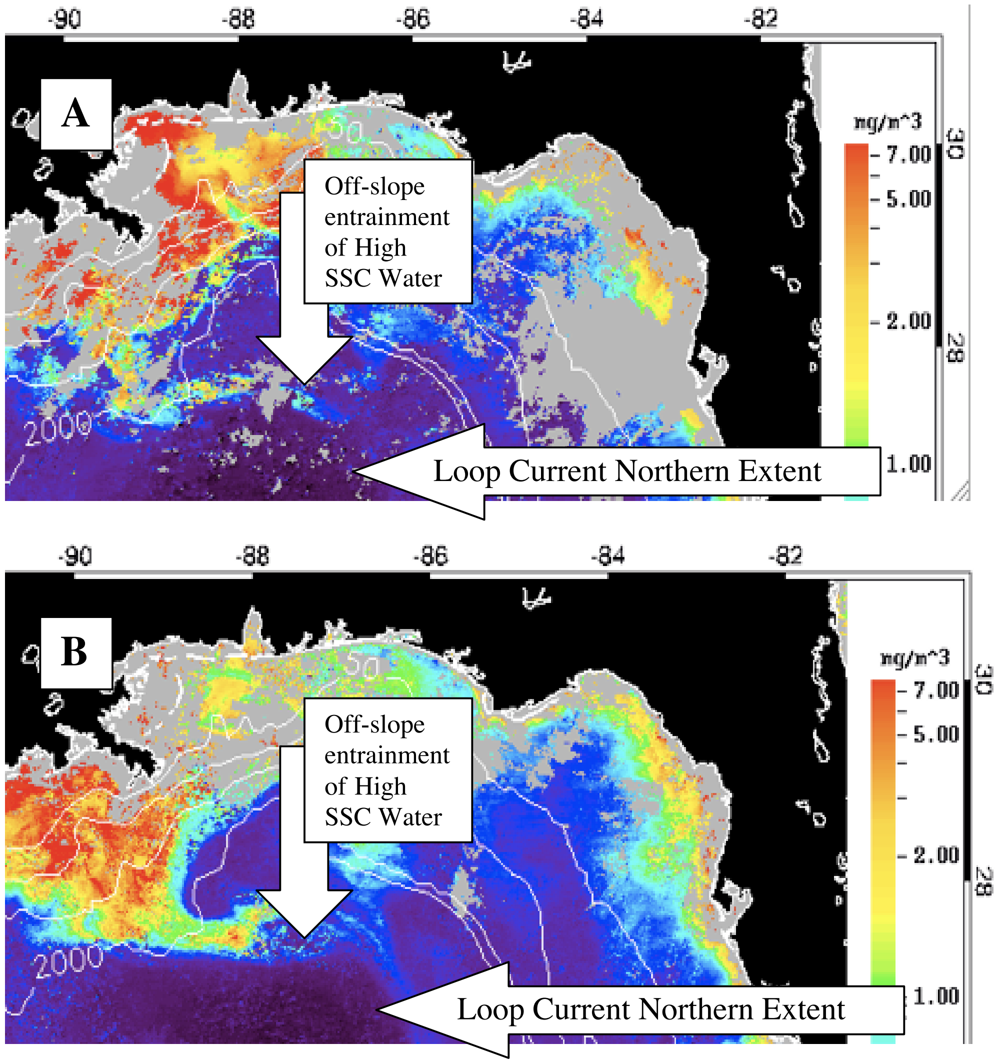

Figure 10. Off-slope entrainment of High SSC Water

A: MODIS 1week composite imagery DOY 197-203, 2004

B: MODIS 1week composite imagery DOY 204-210, 2004

White lines indicate the 50 m, 200 m, 1000 m, & 2000 m isobaths

SSC at the locations of whale encounters also lagged negative SSH and cross-margin flow by 1 week (however, SSH values are composited over an 8-day period with a 0.25° spatial resolution, so the temporal lag between SSH and SSC is not as accurate as the temporal lag between SSC and sperm whale encounters). Whale encounter SSC did not show any relationship to off-margin flow. It seems whales were found in areas that had the potential to be biologically productive over a 4 month period, and that peak SSC in these encounter locations lagged the most negative SSH values by 1 week. Once a cyclone passed over an area of nutrient water (where cross-margin flows had advected riverine output 4 months previously), peak SSC lagged behind the maximum divergence (the most negative SSH) by 1 week. Sperm whales then lagged this peak SSC by 1-2 weeks.

Other studies have tested the association between whales and thermal frontal boundaries and found strong correlations between the two. Griffin (1999) found that sperm whales encountered off Georges Bank appeared to associate with the eastern thermal frontal boundary of a warm core eddy. However, these associations were studied over a relatively persistent eddy without considering a time lag.

In both Griffin (1999) and Doniol-Valcroze et al (2007), whales were not encountered explicitly within the frontal and ring areas. Doniol-Valcroze et al (2007) suggest two possibilities to explain the spatial lag in association. First, frontal areas can often originate several kilometers away from where they are observable at the surface, and this may force deeper-water prey aggregations a certain horizontal distance from the surface frontal manifestation.

The second hypothesis, which is supported by the work of Olson and Backus (1985) with mesopelagic fish, is that a temporal lag may exist between frontal origination and prey aggregation. Oey and Zhang modeled one possible physical means by which this separation in prey aggregation and frontal origination could occur. In their model a subsurface jet is produced approximately 400-200 m below the surface after a cyclone has detached from an LCE near the 1000 m isobath. A mixing front is generated downstream along the jet just days after the parent cyclone has begun frictional interaction with the bottom. A week to two weeks later, intense frontal mixing occurs along the jet, which is the amount of time by which SSC along the cruise track and at whale encounter locations lagged maximum negative SSH. Ten days after mixing has begun and about 3-4 weeks after the cyclone first entered the area, bottom nutrients are brought into shallower, more active layers. Lower regime SSC at locations of whale encounters did not exhibit a similar time lag between SSH, however, lower regime SSC along the entirety of *SummerBreeze's* survey area did lag maximum negative SSH 4 weeks. If the Oey and Zhang model accurately demonstrates the physical method by which cyclones generate surface productivity along their peripheries, SSC at the locations of whale encounters reached its peak about 1 week after maximum negative SSH. This is before frontal generation of new productivity and about the time lag expected to be associated with off-margin transport of high SSC shelf water. However, since whales then lagged maximum SSC by another 1-2 weeks, they were likely encountered in areas where frontal mixing had just begun to advect nutrients into shallower, euphotic layers.

Most studies of sperm whale distribution have attributed the whale's selection of habitat to prey availability (Davis et al 2007, Jaquet and Gendron 2002, Whitehead 1996). This study also finds strong evidence suggesting that the predator prey relationship is an important determinant in sperm whale distribution. Between 2004 and 2005 Gordon et al (2007) found there was a 37% reduction in defecation rate among encountered sperm whales. Whitehead (1996) showed that defecation rates provide a proxy for foraging success. There was a corresponding 30% reduction in geometric mean SSC along the 1000 m isobath between these summers.

Since very little is known about the life histories of cephalopods, it is difficult to judge how oceanographic features important to sperm whale distribution may be influencing their prey aggregation. The association between sperm whales with locally enhanced SSC and sperm whales with areas of cyclonic eddy upwelling could be due not to a higher concentration of prey, but to a greater concentration of preferable, larger prey.

Sthenoteuthis oualaniensis, a tropical ommastrephid, has a two-tiered maturation in which the small form matures before the larger form. Similar situations may arise for other cephalopods in which those found in more productive environments, such as eddy-induced pockets of upwelling, grow faster, attain a larger size and exhibit delayed maturation (Anderson and Rodhouse 2001). Female and juvenile sperm whales off Durban prey on cephalopods of mean weight of 0.5 kg. Adult male sperm whales consume cephalopods that are on average twice as large (Clarke 1996). If a similar difference in prey preference exists between female and male sperm whales in the Gulf of Mexico, this may explain the geographic segregation and distinct SSC time lags between the gender and age based groups.

Aspects of cephalopod biology and behavior may aid a whale's ability to capture prey. Most cephalopods are terminal spawners that aggregate to reproduce, and sperm whales may find it advantageous to feed within spawning grounds when the larger squid are weaker, easier prey (Clarke 1996). Since cephalopods mature rapidly and react to productive environmental conditions quickly, their spawning grounds are generally believed to lie within areas of enhanced biological productivity (Anderson and Rodhouse 2001). Further study of the composition mesopelagic communities in conjunction with sperm whale foraging behavior is needed to assess this possibility.

Physical oceanographic factors may force aggregations of the sperm whale's prey. Doniol-Valcroze et al (2007), using whale sightings and satellite images from 1996-2000 in the Gulf of St. Lawrence, found that rorquals (blue whales) associated within close proximity to thermal frontal boundaries with a frequency of 0.31. The authors cautioned that enhanced primary productivity generated by these frontal boundaries cannot solely explain the rorquals' association with frontal areas, since frontal upwelling can vary spatially over a few days, yet whales were associating with fronts over single days. Instead the authors emphasized that prey species for rorquals (krill and fish) aggregate along the edges of frontal upwelling zones. Krill swim down to avoid the brighter surface light to which the upwelling tends to transport them, while capelin aggregate within narrow thermal bands as they avoid the coldest upwelled water.

In this way, not only are frontal boundaries more productive foraging grounds for rorquals, but they also herd the rorqual prey into more manageable feeding pockets.

Some fish species are strongly influenced by hydrographic features. Tidal current flow over steep gradients can result in strong currents, upwellings, or haloclines which then delay and aggregate Pacific salmon until they are able to re-orient themselves. Atlantic salmon, on the other hand, have been known to orient themselves in relation to areas of current convergence (Hastie et al 2004). Similar effects of hydrography may be felt by cephalopods in the mesopelagic and could explain why sperm whales are sometimes observed to be foraging in less productive, downwelling environments.

Whitehead and Rendell (2004) suggest that foraging strategies differ between clans of whales and may be more closely linked to cultural learning rather than simply a generic response to environmental conditions. In 2005, when reduced Mississippi discharge and northward intrusion of the LC combined to reduce SSC throughout the northeast Gulf, differences in the habitat where groups of sperm whales were encountered became more apparent. Mixed groups of females containing previously identified individuals moved out of the Mississippi Delta and into areas of lower SSC. Groups of newly-identified females were still encountered in the Delta and inhabited areas of significantly higher SSC than the core population groups. Throughout the study area there was a 17% reduction between summers in the percentage of groups containing at least one re-identified individual. Median group size fell by half between summers, as did the percentage of the population comprised by calves.

It is possible that the change is sperm whale composition is due to the effects that productive foraging grounds have on whale behavior. In 2004, sperm whales encountered during legs 3 and 4 were observed to socialize much less than those observed during legs 1 and 2, or to not socialize at all. Mean surface SSC was significantly higher along the cruise track during legs 3 and 4 than legs 1 and 2. When a 2 week time lag is considered, however, mean SSC is only higher before and up until whales are encountered in an area. During the third and fourth legs, two weeks after whales were encountered in an area, whales were found in significantly lower SSC waters than areas surveyed during the first two legs when socializing was more common (Figure 11).

This pattern suggests that whales may be foraging more frequently when they are in areas that have been upwelling over the past two weeks or where productive surface water has been advecting off-margin for the past two weeks. Since biological productivity is spatially and temporally variable in the Gulf, sperm whales likely need to

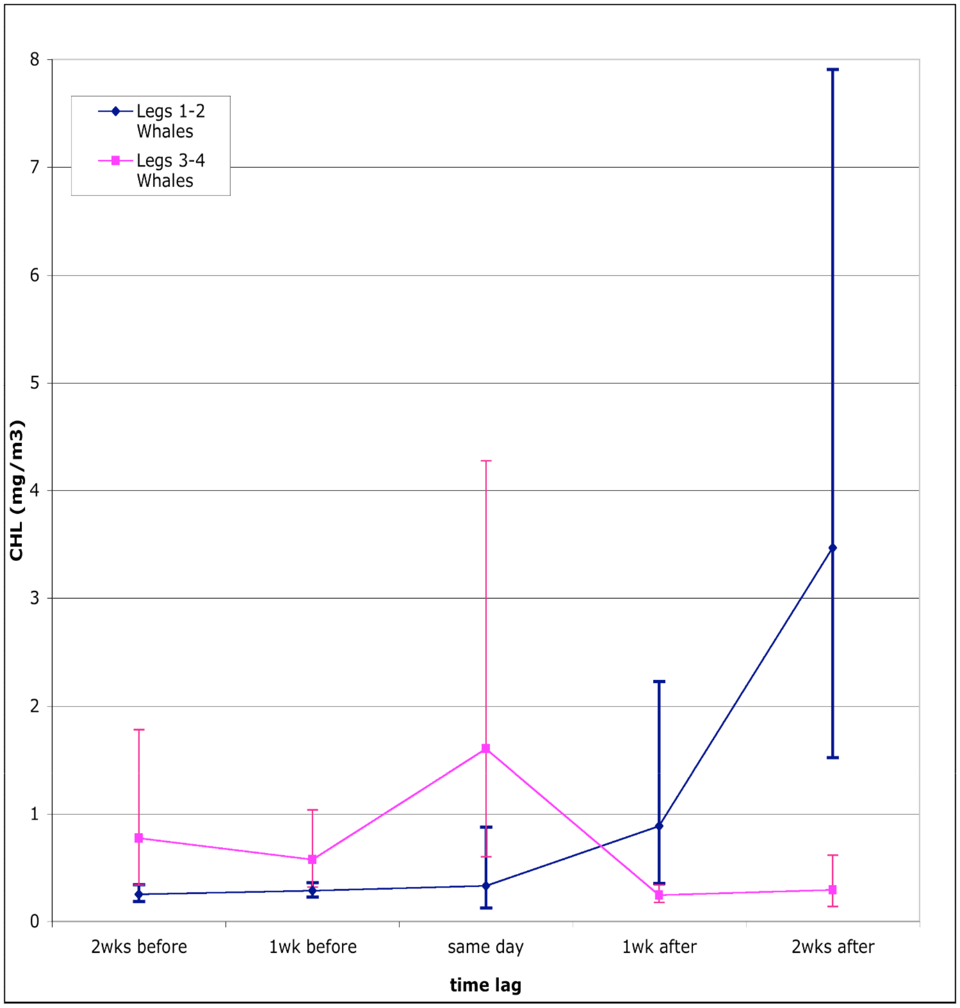

Figure 11. 2004 Mean SSC vs. Time Lag & Socializing Behavior

forage efficiently once they have located productive waters. When whales inhabit areas on the cusp of increased of productivity, i.e. in areas that have not yet begun to spin-up, they may socialize and forage less frequently.

Given the short time lag between surface productivity and sperm whale encounters in the northeast Gulf, similar reductions in both SSC and foraging success and substantial variation in the population composition of sperm whales between 2004 and 2005, it appears that sperm whales in this ecosystem are closely linked with environmental conditions in the surface ocean and at the base of the food chain. Much more research will need to be done regarding mesopelagic ecology, community composition and whale behavior, before we can fully interpret interactions between sperm whales and their habitat. A better understanding of population structure through photo-identification and ship based behavioral observations is especially necessary, as is direct measurement of mesopelagic prey availability. Sperm whales in the northeast Gulf reacted noticeably to oceanographic changes between summers 2004 and 2005, and as apex predators, sperm whales are indicative of the overall health of an entire marine community. In light of impending climate change and changes to our marine environment that will likely take place in future years, it is imperative that we understand how and why communities react to particular environmental conditions.

CHAPTER II

EAST VERSUS WEST VARIABILITY IN GULF OF MEXICO SPERM WHALE DISTRIBUTION AND ABUNDANCE

Introduction

Sperm whale distribution varies from East to West across the northern Gulf of Mexico, as do oceanographic conditions. Mullin and Fulling (2004) surveyed cetacean distribution and abundance across the Gulf of Mexico during NOAA shipboard work conducted over a period of five years (1996-2001), and found more than a five-fold difference in average abundance between northeast and northwest Gulf of Mexico waters. They compared encounters on either side of 88.5ºW for oceanic areas between 200 m depth and extending offshore to the 200 mile limit of the US Exclusive Economic Zone. Sperm whale abundance (and 95% confidence intervals) was estimated to be 99 individuals (42-236) in the northeast Gulf and 558 individuals (275-1131) in the northwest Gulf.

As explained in Chapter One of this thesis, geographic locations of on-margin, off-margin, and along-margin surface circulation in the Gulf of Mexico are affected through a complex interplay of bathymetry, deepwater flow, surface currents, and the mid-water eddy field. Upper layer ocean currents (from the surface down to about 800-1000 m, which is the depth of the Florida Straits sill) are dominated by the Loop Current (LC) and by the Loop Current Eddies (LCEs) that separate from the main flow. These anti-cyclonic LCEs separate at irregular intervals in time, but they usually do so between longitudes 88-89°W. Detachment of these eddies from the LC is associated with energetic fluctuations of subsurface LC motions (Hamilton, 1990). LCEs then translate into the western Gulf where they may cleave into smaller eddies, sometimes through interaction with cyclonic features (Biggs et al, 1996).

As also explained in Chapter One, mid-water and surface eddies are responsible for much of the off-shelf locally high SSC, both through upwelling of mid-water nutrients into the euphoric zone as well as by entrainment and advection of high SSC, low salinity shelf water into deeper water. During summer months when winds are generally westerly, Belabbassi et al (2005) reported that approximately 75% of Mississippi River discharge flowed into the northeastern Gulf. However, Belabbassi et al (2005) judged that most of this wind driven flow impacted continental shelf environments, whereas oceanic areas farthest removed from river mouths were primarily supplied with nutrients from uplift and not from Mississippi River discharge.

Deepwater currents in the Gulf of Mexico are dominated by Topographic Rossby Waves (TRWs). These waves are bottom enhanced and likely influenced by bottom topography (Schmitz et al, 2005). Such waves have periods of ~10-60 days and group speeds of 10-20 km/day which exceed the 3-6 km/day translational speeds of LCEs As TRWs propagate westward through the basin, they become progressively decoupled from surface flows (Hamilton, 1990).

Although the MPS cruise tracks seldom extended west of 92ºW, for this chapter I will consider anything west of 88.5ºW as Western Gulf. Here, bathymetry shoals toward the coast in a northeasterly direction and is bounded on its seaward end by the Sigsbee

Escarpment. MPS eastern cruise track locations fell almost entirely within the Desoto Canyon.

Methods

Methods for obtaining SSC, SSH and SSS values were the same as those explained in Chapter One. To assess linkages between sperm whale encounters and surface oceanography that may be associated with oceanographic differences between the eastern and western portions of the Gulf of Mexico, mean SSC values were recalculated for cruise track locations occurring East of 88.5°W and West of 88.5°W. Mullin and Fulling (2004) selected 88.5°W as the dividing line for their synopsis of sperm whale distribution and abundance. This longitude was also the approximate midpoint in longitude of the 2004 and 2005 MPS *Summer Breeze* cruise tracks.

Results

SSC Means Along 500 m, 1000 m, and 1500 m Isobaths

Mean SSC values calculated along the 1500 m, 1000 m, and 500 m isobaths from 95°W to 84°W showed greater average SSC within the western study area than the eastern area. This trend was especially pronounced during 2004. Throughout summer 2005 off-slope, high salinity/low chlorophyll water or "blue water" dominated along most of the continental margin. Highest SSC waters predominated along the 500 m isobath and decreased seaward toward the 1500 m isobath. As shown in Figure 12, mean SSC in the eastern study area during summer 2004 was

0.29 mg/m3 along the 500 m isobath, 0.18 mg/m^3 along the 1000 m isobath and 0.12 mg/m3 along the 1500 m isobath. During the same summer mean SSC in the western study area was 0.54mg/m^3 along the 500 m isobath, 0.37 mg/m^3 along the 1000 m isobath and 0.21 mg/m^3 along the 1500 m isobath.

In 2004, the eastern and western SSC differences were statistically significant at the 95% CI along the 1000 m and 1500 m isobaths. In 2005, the eastern and western difference was only significant along the 500 m isobath. At all three western isobaths, mean SSC was significantly lower in 2005 than 2004.

Eastern and Western cruise track SSC characteristics are similar to what was historically found in the Gulf. During the Deep Gulf of Mexico Benthos study (DGoMB), which was intended to provide information regarding deepwater ecology potentially impacted by fossil fuel exploration, several stations were sampled for a variety of oceanographic parameters. At DGoMB stations sampled between 86ºW-90ºW and 300-2000 m, geometric mean SSC from 1998-2000 was 0.40 mg/m3 East of 88.5ºW. West of 88.5ºW geometric mean SSC was 0.63 mg/m^3.

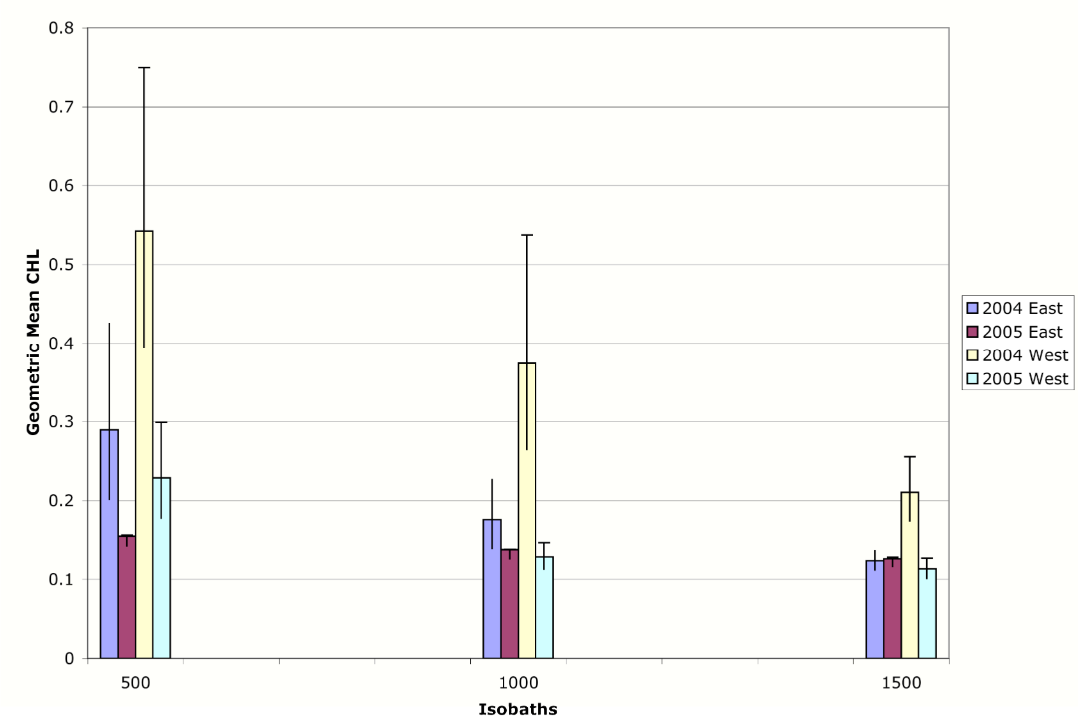

Figure 12. Mean SSC Along Isobaths: 2004 & 2005

Whale Encounters and SSC Means Along the Cruise Track

Table 6. Summary of acoustic and visual survey effort on *Summer Breeze* cruises

Year	Dates of Field Work	Longitude range of continental margin surveyed	Survey Days East or West of 88.5°W Longitude	Groups of Sperm Whales sighted	Individuals Re-sighted from Previous years
2004	June 20 - Aug 15	90.5° – 84.5° W	16 days East 22 days West	6 13	2 24
2005	June 13 – Aug 3	93° – 85°W	12 days East 17 days West	7 9	4 4

Inter-annual differences in the number of groups of whales encountered per day of survey effort were greatest in the eastern Gulf of Mexico (Table 6). In 2005, 7 groups of whales were seen during 12 days of survey effort (search success rate = 0.58/day), compared to six groups per 16 days of survey effort in 2004 (search success rate = 0.38/day). West of 88.5ºW, 9 groups of whales were seen during 17 days of survey effort in 2005 (search success rate = 0.53/day) and 13 groups per 22 days of search effort in 2004 (search success rate = 0.59/day).

Eastern Study Area

Along the 2004 and 2005 cruise tracks, there were generally higher SSC values at eastern whale encounter locations relative to eastern no-encounter locations. Mean SSC differences between encounter and no-encounter locations are most robust when a time lag of 1-2 weeks is taken into account.

In 2004, similar or greater SSC concentrations were generally found at encounter locations during the 2 week period preceding encounters. Figure 13 shows that 2 weeks before sailboat encounters, geometric mean SSC averaged 0.49 mg/m^3. One week before encounters mean SSC was 0.76 mg/m^3, and on the day of encounters mean SSC was 0.52mg/m^3. In contrast, at no-encounter locations geometric mean SSC averaged 0.22 mg/m^3, 0.34 mg/m^3, and 0.33 mg/m^3 for these times, respectively.

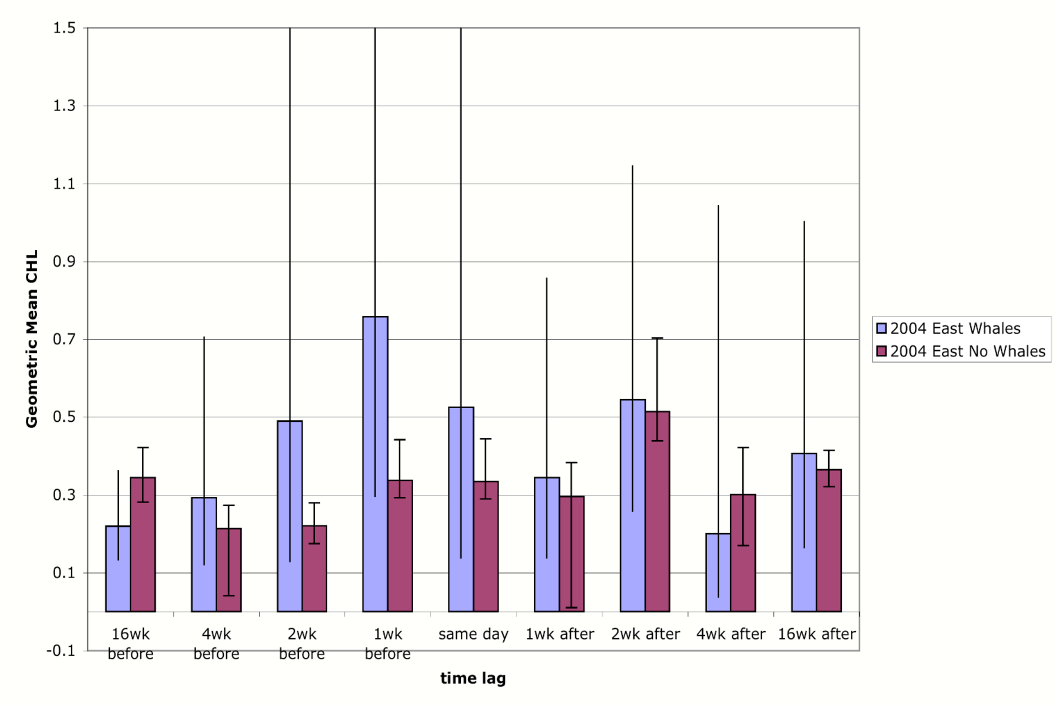

Figure 13. Along Cruise Track Geometric Mean SSC: 2004 East

As Table 7 that follows will show, these were the only time lags with positive and robust ($p \leq 0.07$) correlations between SSC and whale encounters.

Table 7. SSC vs. Whales Correlations: 2004 East

	corrcoef	p value
4 weeks before	0.08	0.500
2 week before	0.28	0.070
1 week before	0.26	0.068
same day	0.37	0.004
1 week after	0.05	0.728
2 week after	0.02	0.898
4 week after	-0.12	0.583

Results for the Eastern study area in 2005 were similar to the previous summer. The 2 weeks prior time lag still had robust differences between mean SSC at encounter versus no-encounter locations. Figure 14 shows that geometric mean SSC at encounter locations 2 weeks prior to sailboat survey was 0.40 mg/m^3 but just 0.18 mg/m^3 at no-encounter locations. On days of encounters, geometric mean SSC at encounter locations remained higher (0.31 mg/m^3 versus 0.18 mg/m^3) than for that of areas where whales were not encountered.

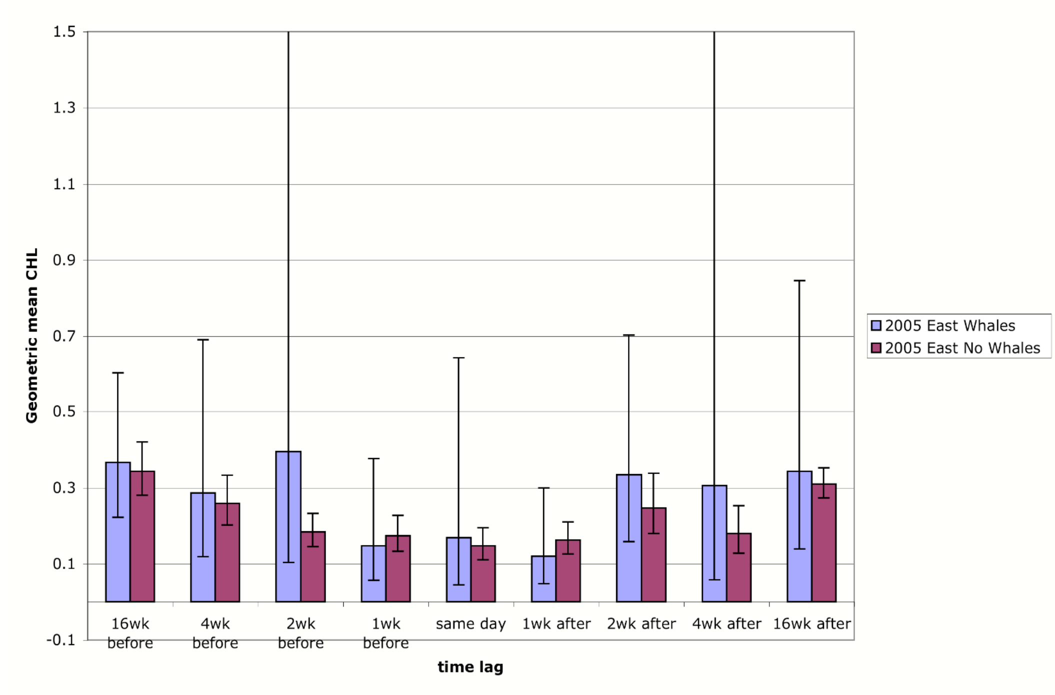

Figure 14. Along Cruise Track Geometric Mean SSC: 2005 East

This pattern is also apparent when correlation coefficients are considered. Table 8 shows that a robust (p<.07) and positive correlation between whales and SSC occurred at the 2 week prior time lag. A second positive correlation also occurs at the 4 week time lag following encounters. This correlation is even greater that the 2 week correlation.

Table 8. SSC vs. Whale Encounter Correlations: 2005 East

	corrcoef	p value
4 weeks before	0.04	0.783
2 week before	0.25	0.071
1 week before	-0.11	0.470
same day	-0.08	0.652
1 week after	-0.18	0.220
2 week after	0.17	0.212
4 week after	0.45	0.006

When whale encounters and mean SSC were averaged over both 2004 and 2005, Table 9 shows that the only statistically significant correlation was a positive correlation indicating a 2 week time lag between SSC and whale encounters.

Table 9. SSC vs. Whales Correlations: Combined Summers East

	corrcoef	p value
4 weeks before	0.08	0.430
2 week before	0.25	0.015
1 week before	0.07	0.466
same day	0.09	0.428
1 week after	-0.11	0.272
2 week after	0.02	0.801
4 week after	0.11	0.413

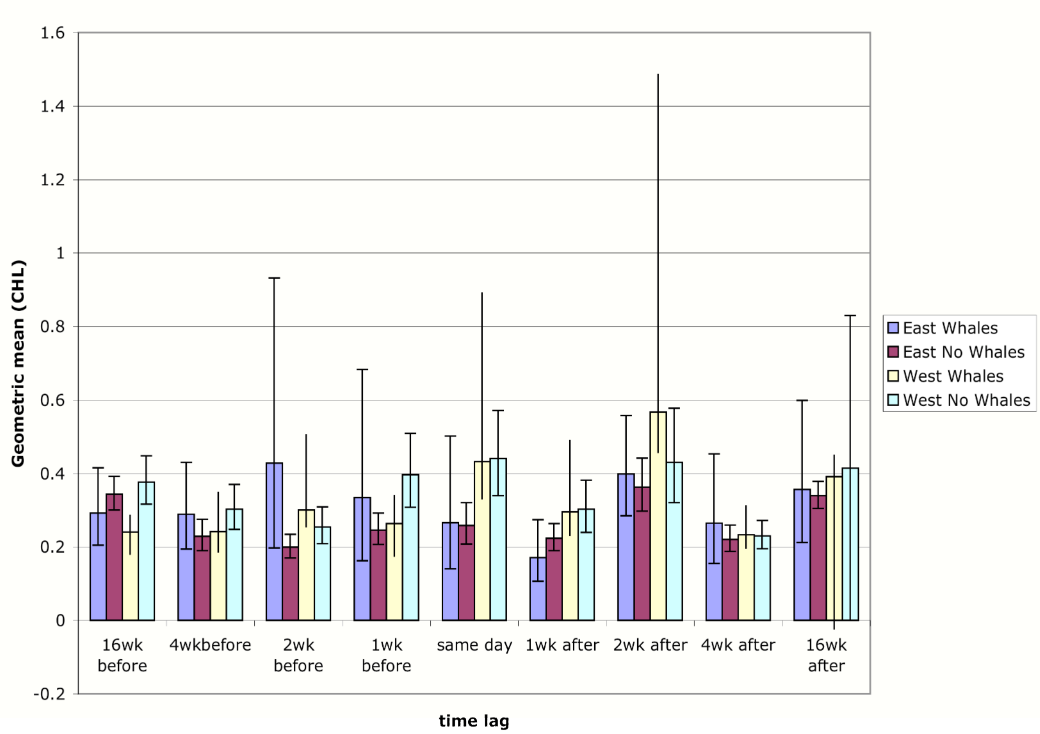

Figure 15. Along Cruise Track Mean SSC: Combined Summers

Figure 15 shows combined summer geometric mean SSC for East and West whale and no whale encounters. Whale encounter locations in the West had mean SSC levels that were significantly greater than no encounter locations in the East at the ±2 week and zero time lags. At the time lag preceding whale encounters by 16 weeks, the East no encounter SSC mean is significantly higher than the West encounter mean.

In terms of Sea Surface Salinity (SSS), Figure 16 reveals that the 2005 eastern track was relatively unchanged from 2004. SSS along the 2004 eastern cruise track at whale encounter locations was higher than the 2005 encounter locations at all time lags. At negative encounter locations SSS was generally the same between summers. During 2004, SSS was higher at locations of whale encounters than locations of no encounters at the ±1 week and zero time lags. Locations of whale encounters during summer 2005 were of lower SSS than no encounter locations at the ±2, ±1 week and zero time lags.

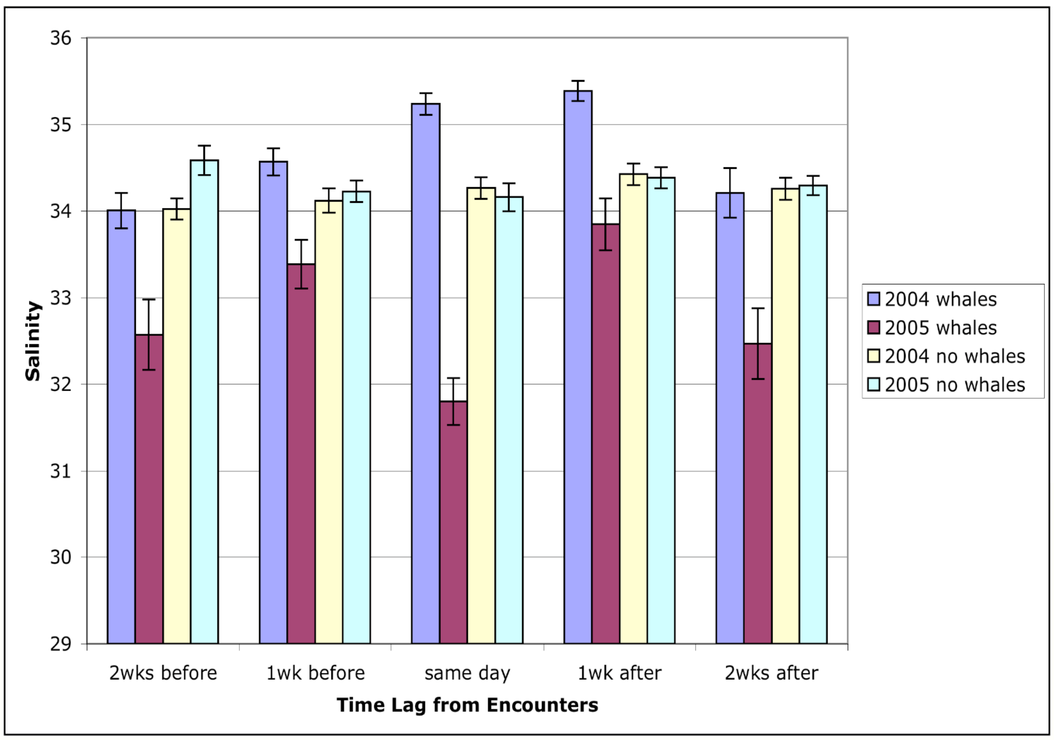

Figure 16. Along Cruise Track Mean SSS: East

Western Study Area

Encounters in the western study area do not show the same relationship to SSC as those in the East. West of 88.5ºW, there were minimal differences in geometric mean SSC values between whale encounter and no-encounter locations, (2 weeks prior to an encounter there was on average 0.30 mg/m^3 compared to 0.25 mg/m^3 at negative encounter locations). Figure 17 shows that SSC differences were not statistically different at the 95%CI from those at no-encounter locations.

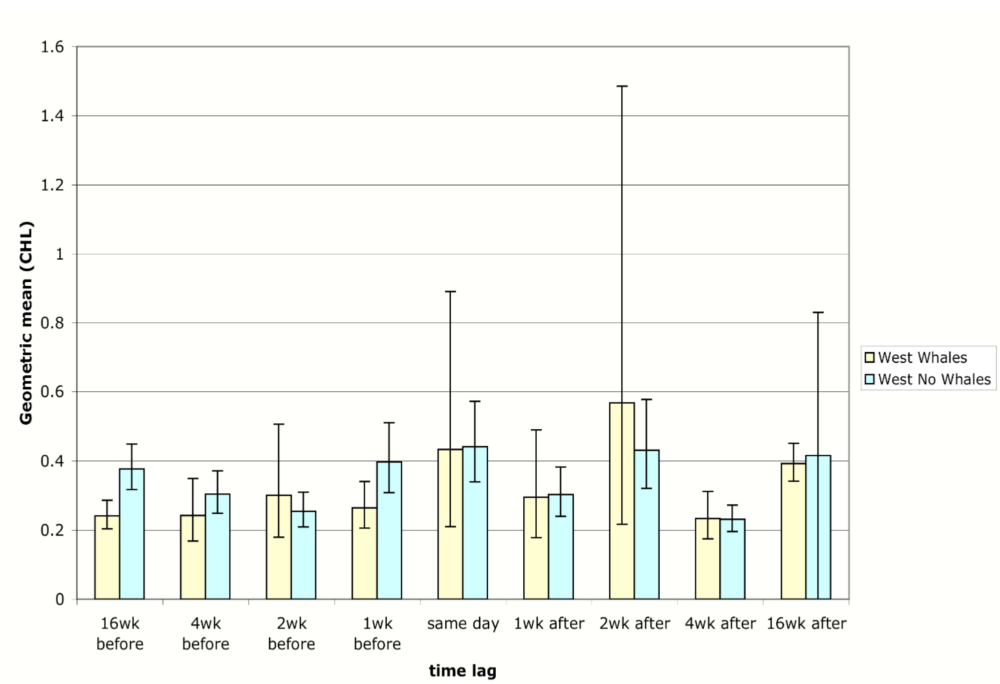

Figure 17. Along Cruise Track Mean SSC: Combined Summers West

The only statistically significant correlation between whale encounters and SSC west of 88.5°W was negative and occurred when no time lag was considered (Table 10).

Table 10. SSC vs. Whale Encounter Correlations: Combined Summers

	corrcoef	p value
4 week before	-0.09	0.300
2 week before	0.03	0.780
1 week before	-0.14	0.150
same day	-0.24	0.005
1 week after	-0.06	0.462
2 week after	-0.01	0.903
4 week after	-0.03	0.741

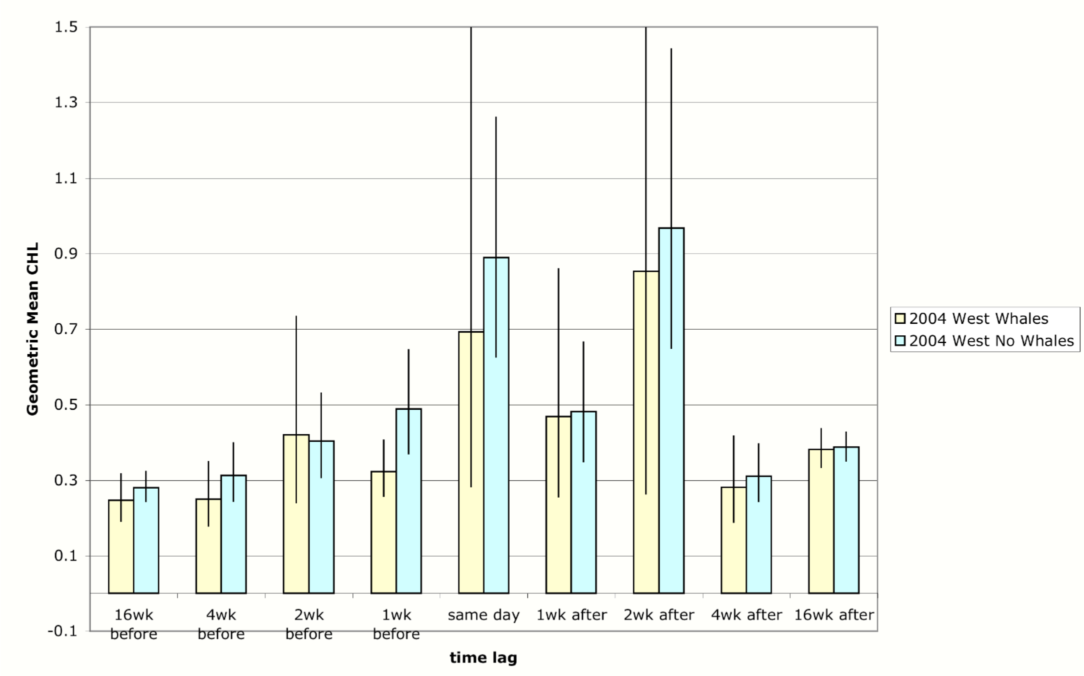

Figure 18. Along Cruise Track Mean SSC: 2004 West

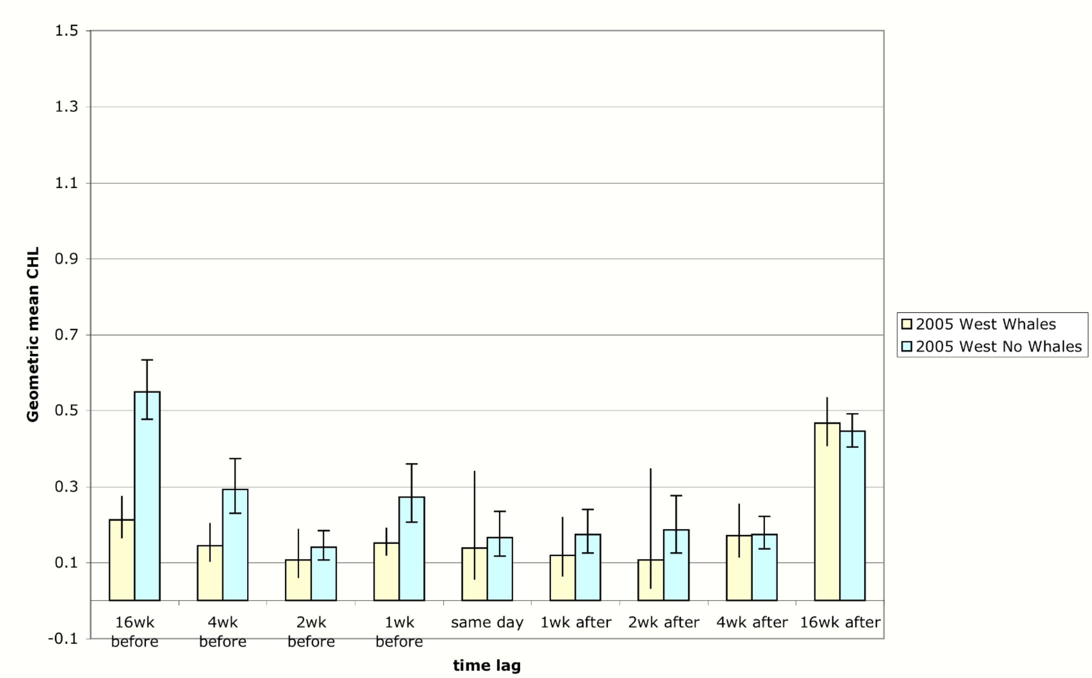

Figure 19. Along Cruise Track Mean SSC: 2005 West

Figure 18 represents geometric mean SSC in 2004 at whale and no whale encounter locations for each time lag. In 2004, there were no differences between mean SSC at encounter versus no-encounter locations.

During 2005, the only statistically significant differences between SSC at encounter versus no-encounter locations were at time lags of 16 weeks previous, 4 weeks previous, and 1 week previous to encounters. At each of these time lags mean SSC at no-encounter locations was significantly greater than at locations where whales were encountered (Figure 19).

Even though there was no relationship between SSC and whale encounters in the western study area of the Gulf, in 2004 the mean SSC in the western region increased with time. Figure 20 shows that at encounter as well as at no-encounter locations, SSC increased from two weeks before to two weeks after sailboat survey.

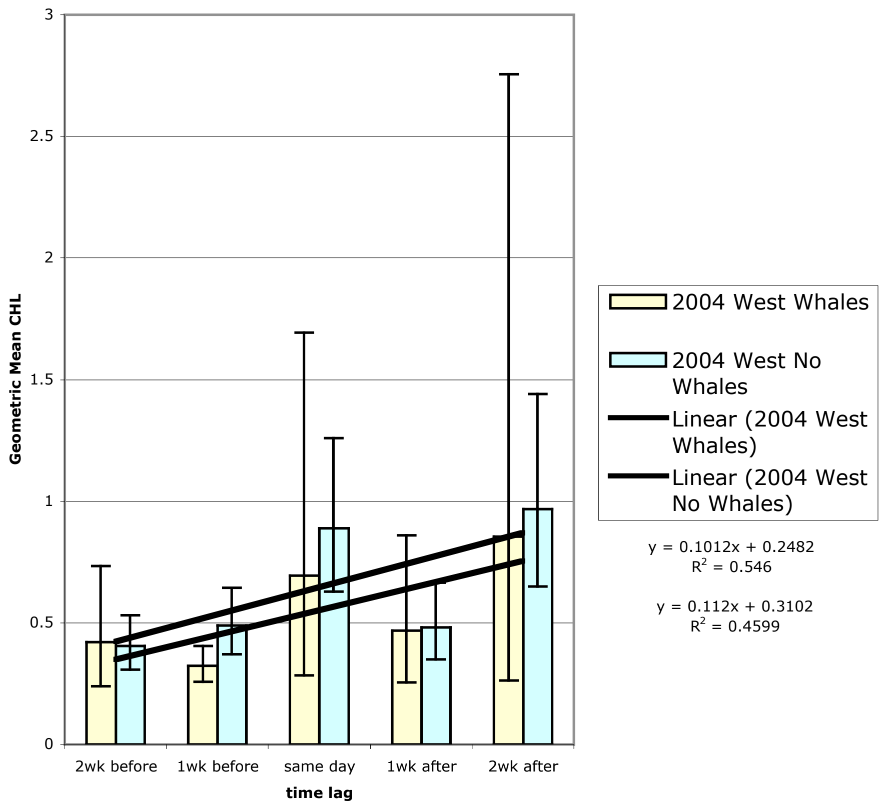

Figure 20. One Month Along Cruise Track Mean SSC: 2004

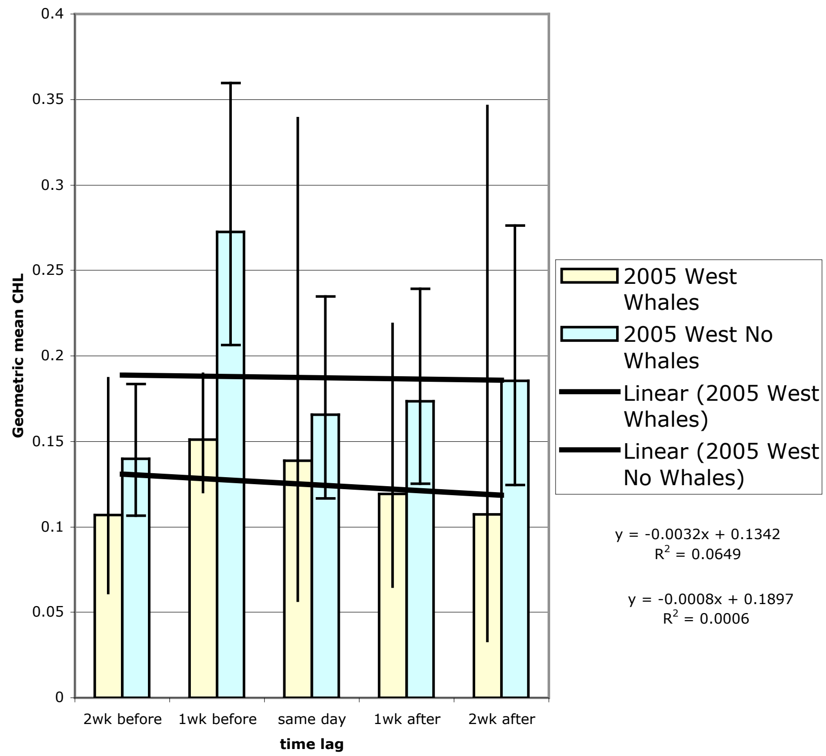

Figure 21. One Month Along Cruise Track Mean SSC: 2005

Throughout summer 2005, when blue water was the rule along both western and eastern portions of the survey track, no build-up of SSC was seen within the western study area. Figure 21 shows that geometric mean SSC averaged $\leq$ 0.2 mg/m^3 at both encounter and no-encounter locations, from two weeks before to two weeks after sailboat survey.

Mean SSS at 2004 whale encounter locations, as shown in Figure 22, was lower than that for 2005 encounter locations by over 2 units. Mean SSS at locations of whale encounters was higher than mean SSS at no encounter locations for both summers.

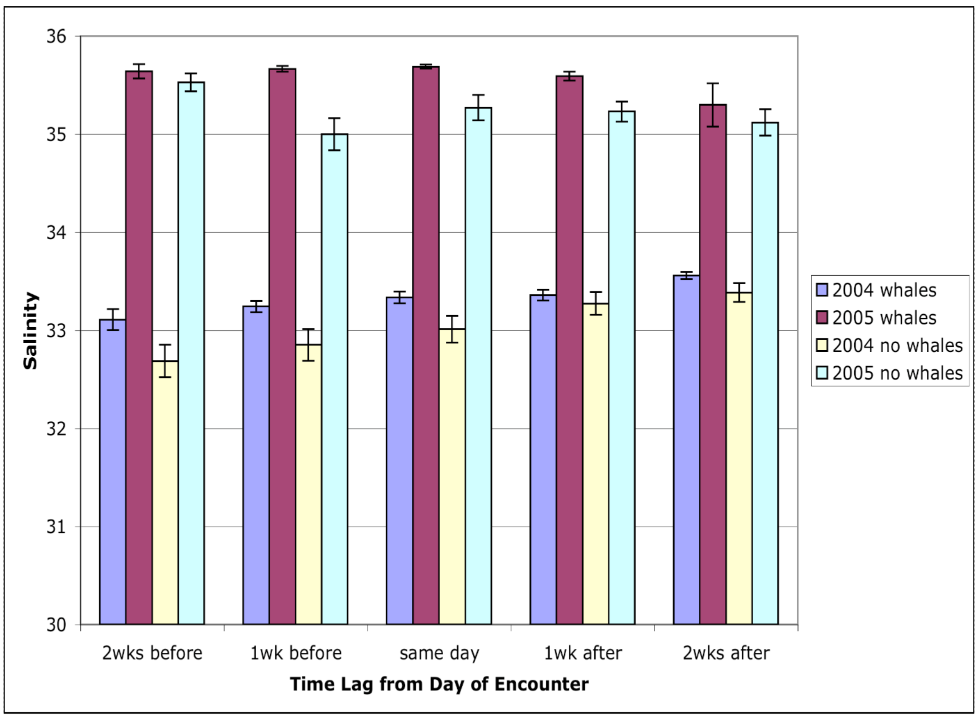

Figure 22. Along Cruise Track Mean SSS: West

Discussion

Distinct oceanographic differences exist from East to West across the northeastern Gulf of Mexico. However, the relationship between these oceanographic differences and sperm whale behavior is less clear. Sperm whales segregate geographically across the northern Gulf. Females, particularly core population females, exhibited fidelity toward the Mississippi Delta and western study area. Male whales were generally observed in the eastern portion of the study area, which encompassed the Desoto Canyon. Between 2004 and 2005, there was very little change in the number of whales encountered within this eastern study area, though the number of whales encountered per day of survey effort was markedly reduced.

At least 6 of the groups encountered during 2005 contained males, compared with just 4 groups in 2004, two of which contained the same male individual. Four of the 6 male groups encountered during 2005 fieldwork were encountered in the eastern Gulf. Three of the 4 male groups found during summer 2004 were encountered in the eastern Gulf.

Group composition of sperm whales appears to have been even further affected between summers. In 2004, 24 individual whales were re-sighted in the western Gulf compared to just 2 in the eastern Gulf. However, in 2005 Western Gulf resightings numbered 5 and 4 in the eastern Gulf. In other words, while there was a 36% reduction in the number of groups encountered and a 44% reduction in the number of resighted individuals between summers across the entire study area, in just the western portion there was a 75% reduction in the number of resighted individuals. The eastern Gulf resightings actually numbered two more in 2005 than in 2004.

Mean SSC along isobaths and cruise tracks is lower in the East than west, however inter-annual variation in SSC was less drastic in the East than West. Western study area SSC was more noticeably reduced between summers, and in addition to the West's reduced SSC, summer 2005 also lacked a month-long build-up of SSC along the cruise track.

The 2004 West had statistically higher mean SSC at its 1000 m and 1500 m isobaths compared to its eastern isobath counterparts. In 2005, these isobaths had nearly equal mean SSC across the Gulf. Only at the 500 m isobath did western SSC remain statistically greater than eastern SSC during summer 2005, demonstrating the flushing of the northern Gulf with off-slope, blue water.

Mean SSS model output highlights the effects of the Loop Current's 2005 northward extension. Western SSS was over 2 units higher in 2005 than in 2004 (~35.6 vs. 33.4) at whale encounter locations. In the East the opposite change in mean SSS occurred. Mean SSS in 2005 at whale encounter locations was over 3 units lower than 2004 whale encounter mean SSS (31.7 vs. 35.2). From this model output and satellite imagery it appears that the entrainment and off-slope transport of high-SSC water was affected through interaction of a cyclone-anticyclone pair in 2004 and that the entrained shelf water was largely confined to the western study area. In 2005, the LC's northward extension forced Eddy Vortex and its peripheral cyclones further up-slope and further toward the Mississippi Delta. Interaction of these cyclone-anticyclone pairings entrained and transported shelf water through the eastern rather than western study area.

At the 1000 m and 1500 m isobaths, the 2004 eastern portion, 2005 eastern portion, and 2005 western portion have statistically equal mean SSC. The number of whale groups encountered within these areas were 6, 7, and 9 respectively. Thirteen groups of sperm whales were encountered within the 2004 West. Where there was the greatest change in SSC, the 2004 West, there was a corresponding change in the number of groups of whales. From 2004 to 2005, there was a 31% reduction in the number of different groups observed in the western study area and a 34% reduction in mean SSC along the 1000 m isobath.

Oceanographic variation between summers permits several observations about sperm whale distribution in the northeastern Gulf of Mexico. First, partitioning of habitat is important. Groups of females and groups of males are geographically segregated and this boundary occurs within the Mississippi Delta. Even during summer 2005 when steep physical and biological changes were taking place in the sperm whale's habitat, overlap of male and female groups only occurred near their usual boundary.

Sperm whale abundance and distribution is closely linked to surface primary productivity on time scales of a few days to a couple of weeks and spatial scales resolved by current remote sensing technology (3-9km). For an apex, deep-diving marine mammal, this finding is not necessarily expected and indicates that sperm whale prey likely associate with areas of enhanced surface productivity.

Lastly, while mean conditions across the northeastern Gulf vary from East to West, sperm whales actively locate pockets of similar levels of surface productivity. Whale encounter locations on the day of encounter did not differ significantly in mean SSC in the East compared to the West. Mean SSC at whale encounter locations was significantly lower in the East than the West at the 1-2 week time lags. When these time lags of 1-2 weeks were considered, whale encounters in the East positively correlated with higher SSC. Whale encounters in the West did not demonstrate a similar positive correlation to SSC, and this may be an indication of different foraging strategies between either genders/groups or geographic locations. While whales in the West appear to be more effected by large-scale (in both space and time) surface productivity, it appears that more local, small-scale productivity is what is important for whales in the East. The striking change in number and distribution of core population female and male groups between summers suggests that the sperm whale's relationship to surface primary productivity and foraging strategy is more closely related to gender and or group membership, rather than geographic location.

CHAPTER III

SUMMARY AND CONCLUSIONS

Sperm whale habitat in the northern Gulf of Mexico is heavily influenced by small-scale environmental variability operating over relatively short time scales. Oceanographic mesoscale variability induced by the Loop Current (LC) and its associated eddy field both enhances and mediates surface observable variations within the Gulf. During summers 2004 and 2005, several oceanographic processes played an important role in affecting sperm whale distribution between the Mississippi Delta and Desoto Canyon.

Physical oceanography in the Gulf of Mexico is dominated by the effects of the LC. Year to year, LC penetration into the Gulf fluctuates in its northward extent, which in turn establishes a basin-wide eddy field that is variable in both space and time (Leben 2005). Anti-cyclonic, warm-core eddies shed stochastically from the LC and propagate into the central and western Gulf, where they may generate or be modified by cyclonic, cold-core eddies (Schmitz et al. 2005). Sea Surface Chlorophyll (SSC) as determined from satellite data was generally highest along cyclonic frontal boundaries. Sea Surface Salinity (SSS) as modeled by the Naval Research Laboratory was generally highest along cyclonic and anti-cyclonic frontal boundaries. Cyclones are areas of divergence where upwelling action can bring nutrients into the euphotic zone and spur primary production, which then creates locally enhanced SSC in these areas.

Mississippi River discharge contributes an important source of nutrients to the northern Gulf and is another important factor effecting primary production. In 2005, river outflow was more than one standard deviation below its 25-year mean (Biggs and Jochens, in review). Summer 2005 also saw a northward extension of the LC that produced an anti-cyclonic, warm-core eddy, named Eddy Vortex, along the 1000 m isobath in the Mississippi Delta and Desoto Canyon areas. These variables combined to reduce SSC by 30% along the 1000 m isobath in the northeast Gulf.

Between summers 2004 and 2005, the distribution of sperm whale groups was noticeably different. Members of the Gulf's 'core population,' female sperm whales identified at least twice throughout the past 10 years of cetacean surveys, usually tended to cluster near the Mississippi Delta, particularly along the 1000 m isobath. In contrast, groups identified by researchers as containing juvenile males mainly inhabited the Desoto Canyon, which was searched during the eastern portion of 2004 and 2005 surveys. In 2004, these usual patterns were observed by the *SummerBreeze* crew. Approximately 32% of individuals identified by high-quality photographs in June-July 2004 had been previously encountered in the Gulf of Mexico, and over half of the groups (58%) included at least one previously identified individual. These re-identified whales were found in waters of similar SSC to other whales that were newly identified in 2004.

Summer 2005, however, was markedly different. The Mississippi Delta was flushed with on-margin, high salinity water and the 1000 m isobath was dominated by anti-cyclonic rotation from the northward intrusion of the LC. Core population groups were encountered both east and west of the Delta, but male groups were found further west, and only 15% of the individuals (38% of groups) had been previously encountered in the Gulf. Re-identified whales were usually associated with groups that were encountered in waters of lower SSC than newly identified whales. Median group size also fell from 13.7 in 2004 to 6.8 in 2005. The percentage of the population comprised by calves fell by over half (12.7% to 5.7%).

Oceanographic changes between summers were most noticeable west of 88.5ºW. Here, geometric mean SSC along the 1000 m isobath fell by 68% from summer 2004 to summer 2005. In contrast, SSC east of 88.5ºW along the 1000 m isobath was relatively unchanged between summers. Mixed groups of females and juveniles were encountered at a higher rate in the western portion of the cruise track in 2004 compared to the eastern cruise track. During 2004, geometric mean SSC was over 50% greater along the western portion of the 1000 m isobath than the eastern portion. West of 88.5ºW, geometric mean SSC in areas of no whale encounters was not statistically different from mean SSC in locations of whale encounters.

This geographic segregation between genders suggests that female sperm whales in the Gulf were associated with SSC on a spatial mesoscale at least as large as the Mississippi Delta survey area. In 2005, when SSC in this area fell by 50%, fewer core population groups were found, and those that were encountered in 2005 appeared to seek what cyclonic frontal boundaries did exist. For example, two groups that were followed near 93°W contained members of the core population, in an area where there was a pair of weak, interacting cyclones. Groups of females of newly identified individuals were found in the Delta where SSC was still apparently higher than surrounding areas, since these whales were encountered in areas of higher mean SSC than the core population groups that may have moved either offshore or to the far West and East. For the core population groups, association with divergent zones of cyclonic upwelling may be more important than maintaining their position within the Delta or areas of generally high SSC. The high SSS coupled with whale encounter locations within the western survey area during both summers suggests that previously-encountered whales may prefer divergent areas where upwelling is taking place.

Males, on the other hand, while usually found east of 88.5°W and in areas of overall lower mean SSC than core population female groups, had much stronger associations with SSC over time scales of a couple days to weeks and spatial scales of just a few kilometers. Male groups during both summers were observed within frontal boundaries between eddies or along anti-cyclones where high SSC, low salinity water was entrained and transported off-margin.

Such geographical separation between groups of whales may effect gender-based differences in foraging strategies or foraging success. Sperm whales, prior to a deep foraging dive, make a characteristic fluke-up, which allows researchers to photograph the underside of their tail flukes for individual identification (Gordon et al 2007). Often during fluke-ups, a sperm whale will defecate, and so defecation rates have been proposed as a useful proxy for foraging success (Whitehead 1996). Between 2004 and 2005, defecation rates among groups of sperm whales in the northeast Gulf fell by 37%, as compared to a 30% decrease in SSC along the 1000 m isobath.

In the broadest context, associations between sperm whales and surface oceanographic features and productivity in the Gulf of Mexico are likely to be more complicated than a simple linear correlation between whales and SSC. Areas of whale encounters and the oceanography of those areas varied between groups and genders. In order to understand and manage habitat important to sperm whales as well as other cetaceans, it will be necessary to more fully quantify the population behavior and community dynamics of these animals. Continuation and extension of the Mesoscale Population Study of sperm whales in the Gulf of Mexico during summer 2008 and beyond is necessary to better understand interannual variability and its impact on the marine community.

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VITA

Julia Elizabeth O’Hern
Texas A&M University
Department of Oceanography
juliaohern@tamu.edu

Education B.A. Cornell University, Ithaca, NY; 2002-2005
Major: Science of Earth Systems with Ocean Science concentration
Major: Government with American Government concentration

Research Cruises/ Fieldwork

- Methods Controlling Hypoxia: LUMCON Ship *Pelican*, Sept. 2007, 4 days: CTD rosette deployment & recovery, plankton tows, water sample and record-keeping.
- Gulf of Mexico East Coast Carbon Cruise: NOAA Ship *Ronald H. Brown,* July 2007, 26 days: Research Assistant to Dr. Shari Yvonn-Lewis: water sample collection and analysis of halogenated carbon samples with a Gas Chromatograph-Mass Spectrometer. Completed regular hydrophone acoustic listening stations for cetaceans.
- Galapagos Cetacean Survey: Oceanographic Institute of the Ecuadorian Navy ship *Rigel*, May 2007: Acoustic cetacean surveys using an underwater, over-the-side hydrophone and analogue recorder and visual behavioral observations
- Western Boundary Current Time-Series: NOAA Ship *Ronald H. Brown*, March 2006 & 2007, 21 days & 19 days: Research Assistant to Dr. Shari Yvon-Lewis
- Merrimack Plume: R/V *Lucky Lady*, Merrimack River: May 2006 & 2007, 3 & 5 days: operation of a towed CTD and underway ADCP.
- Gulf of Mexico: R/V *Gyre*, Gulf of Mexico, Aug. 2005: plankton tows, 3 days
- Cornell University Field Program in Earth and Environmental Systems, Spring 2004: deployment of a buoy hydrophone array; terrestrial field surveys
- Shoals Marine Laboratory, Summer 2001: transect study along the Appledore Island intertidal zone as part of a 19 year, on-going transect study.

Publications and Oral Presentations

- “ECOLOGY OF INCREASING DISEASES: POPULATION GROWTH AND ENVIRONMENTAL DEGRADATION” Human Ecology, 2007
- Published abstract. “INTERANNUAL DIFFERENCES IN ENCOUNTERS WITH SPERM WHALES IN THE GULF OF MEXICO SUMMERS 2004 AND 2005” ASLO 2007 Aquatic Sciences Meeting: Santa Fe, New Mexico; Feb. 4-9 2007: Oral presentation of thesis research as part of the Apex Predators and Trophic Relationships session

Skills, Awards, Professional Societies
PADI SCUBA Advanced Open Water
Texas Aggie Storm Chasers
Texas A&M Sailing Team
Proficiency in Spanish
Scherck/Sharp Fellowship, 2007-2008